Design and Development of Cellular Structure for Additive Manufacturing

A Thesis Submitted in Partial Fulfilment of the
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by

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CERTIFICATE

This is to certify that the thesis entitled, "**Design and Development of Cellular structure for Additive Manufacturing**" being submitted by **Biranchi Narayan Panda** for the award of the degree of **Master of Technology (Research) Degree** of NIT Rourkela, is a record of bonafide research work carried out by him under my supervision and guidance. He has worked for more than two years on the above problem at the Department of Industrial Design, National Institute of Technology, Rourkela and this has reached the standard fulfilling the requirements and the regulation relating to the degree. The contents of this thesis, in full or part, have not been submitted to any other university or institution for the award of any degree or diploma.

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This Thesis Dedicated to Sai Baba

And My Parents

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For every right ACTION, there is equal right OPPORTUNITY

-----------Mina Tadros

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Life isn't a matter of milestones but of moments.

--- Rose Fitzgerald Kennedy

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---------*Biranchi Narayan Panda*

ABSTRACT

The demand for shorter product development time has resulted in the introduction of a new paradigm called Additive Manufacturing (AM). Due to its significant advantages in terms of cost effective, lesser build time, elimination of expensive tooling, design flexibility AM is finding applications in many diverse fields of the industry today. One of the recent applications of this technology is for fabrication of cellular structures. Cellular structures are designed to have material where it is needed for specific applications. Compared to solid materials, these structures can provide high strength-to-weight ratio, good energy absorption characteristics and good thermal and acoustic insulation properties to aerospace, medical and engineering products. However, due to inclusion of too many design variables, the design process of these structures is a challenge task. Furthermore, polymer additive manufacturing techniques, such as fused deposition modeling (FDM) process which shows the great capability to fabricate these structures, are still facing certain process limitations in terms of support structure requirement for certain category of cellular structures. Therefore, in this research, a computer-aided design (CAD) based method is proposed to design and develop hexagonal honeycomb structure (self-supporting periodic cellular structure) for FDM process. This novel methodology is found to have potential to create honeycomb cellular structures with different volume fractions successfully without any part distortion. Once designing process is complete, mechanical and microstructure properties of these structures are characterized to investigate effect of volume fraction on compressive strength of the part. Volume fraction can be defined as the volume percentage of the solid material inside the cellular structure and it is varied in this thesis by changing the cell size and wall thickness of honeycombs. Compression strength of the honeycomb structure is observed to increase with the increase in the volume fraction and this behavior is compared with an existing *Wierzbicki* expression, developed for predicting compression properties. Some differences are noticed in between experimentally tested and *Wierzbicki* model estimated compressive strength. These differences may be attributed to layer by layer deposition strategy and the residual stress inherent to the FDM-manufacturing process.

Finally, as a design case study, resin transfer molding (RTM) mold internally filled with honeycomb is designed and tested instead of the regular FDM mold. Results show that our

proposed methodology has the ability to generate honeycomb structures efficiently while reducing the expensive build material (Mold) consumption to near about 50%. However, due to complex geometry of the honeycomb pattern the build time increased about 65% compare to solid FDM mould. In this regard, FDM tool-path can be optimized in future, so that overall product cost will be minimized.

As per the author's knowledge, this design methodology will have a greatest contribution towards creating sustainable and green product development. Using this, in future, expensive build material and production time can also be minimized for some hydroforming and injection molding applications.

Keywords: Computer-aided design (CAD), Cellular structures, Resin Transfer Molding (RTM), Design for Additive Manufacturing (DFAM)

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List of Acronyms

ABS Acrylonitrile butadiene styrene

AM Additive Manufacturing

CLS Cellular lattice structure

CAD Computer aided design

CNC Computer numerical control

CATIA Computer aided three-dimensional interactive application

DFAM Design for Additive Manufacturing

EBM Electron beam machining

FEA Finite element method

FDM Fused deposition modelling

RP Rapid Prototyping-

RTM Resin transfer molding

SLS Selective laser sintering

SLA Stereolithography

Chapter 1

INTRODUCTION, BACKGROUND AND MOTIVATION

1.1 Overview

The demands for lighter, stronger, and more customizable parts have necessitated the research and development of new technologies, tools, and methodologies that can satisfy the new demands of the modern world. In this regard, the advent and continual improvement of one technology, additive manufacturing, has dramatically changed the way engineers pursue design and manufacturing. Additive manufacturing, once referred to as Rapid Prototyping (RP), has been used in many diverse field of industry for verifying the concepts (concept modeling) prior to production. However, with advancement of material science, this new and promising technology has eliminated many barriers to manufacturing and has allowed designers to achieve a level of complexity and customizability that is infeasible using traditional machining processes. As a result, most of the industries like Siemens, Phonak, Widex, Boeing and Airbus are now using this technology for producing their functional parts that are used in the final products. One such application of this technology is for manufacturing of customized, lightweight cellular structures. They have several advantages such as high strength-to-weight ratio and strong thermal and acoustic insulation properties. These types of structures are suitable for any weight-critical applications, particularly in the aerospace and automotive industries. This research will present a method for the design of these cellular structures for mold making application.

1.2 Background

1.2.1 Additive Manufacturing

Additive manufacturing (AM) is an additive fabrication process where a three-dimensional part is produced by stacking layers of thin 2-D cross sectional slices of materials one over another without use of tooling and human intervention. The process begins with a solid model CAD drawing of the object. The CAD model is then converted in to .STL file format and sent to an AM machine for prototype building [1]. The whole process of design to physical model through various intermediate interfacing stages is shown in Fig. 1. These steps are common to most AM systems but the mechanisms by which the individual layers are created depend on the specific system.

Currently, many technologies exist that into the broad definition of AM. These technologies are supported by various distinct process categories. These are: photo polymerization, powder bed fusion, extrusion-based systems, printing, sheet lamination, beam deposition, and direct write technologies [2, 3]. Each of these processes has its own distinct set of advantages and disadvantages regarding characteristics such as surface finish, manufacturing speed and layer resolution. Of these different processes, three technologies are most commonly used: fused deposition modeling (FDM), stereolithography (SLA) and selective laser sintering (SLS). These three processes will be briefly outlined in the following sections.

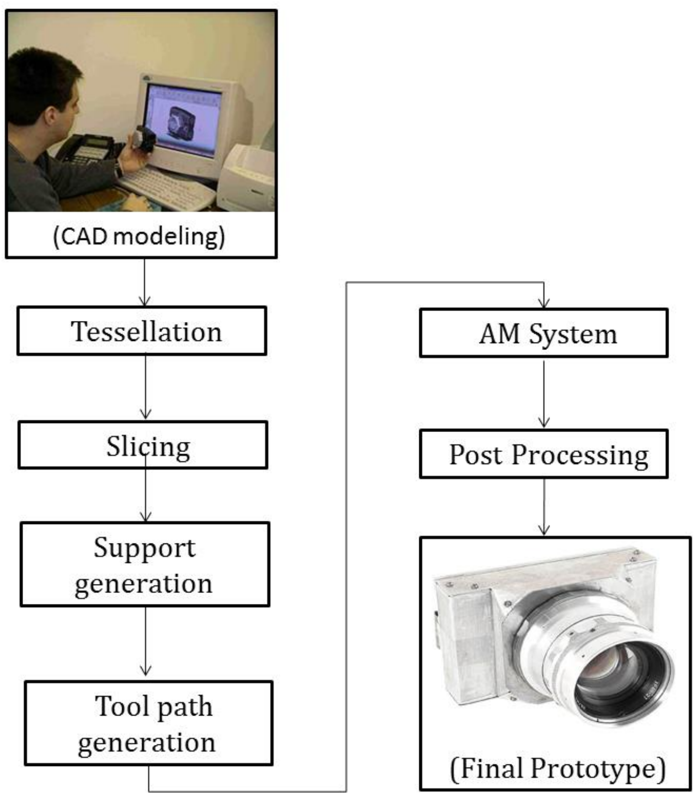


Fig. 1 CAD-Prototype intermediate stages

1.2.1.1 Fused Deposition Modelling (FDM)

Fused Deposition Modelling (FDM) was introduced and commercialized by Stratasys, Minnesota, USA in 1991.FDM process builds prototype by extruding material (normally thermoplastic like ABS) through a nozzle that traverses in X and Y to create each two dimensional layer. As each layer is extruded, it bonds to the previous layer and solidify. The platform is then lowered relative to the nozzle and the next slice of the part is deposited on top of the previous slice. A second nozzle is used to extrude a different material in order to build-up support structures for the part where needed. Once the part is completed, the support structures are broken away from the part [4, 5]. Fig. 2 shows a schematic diagram of FDM Process, where blue color indicates the model material and red color points to the support material.

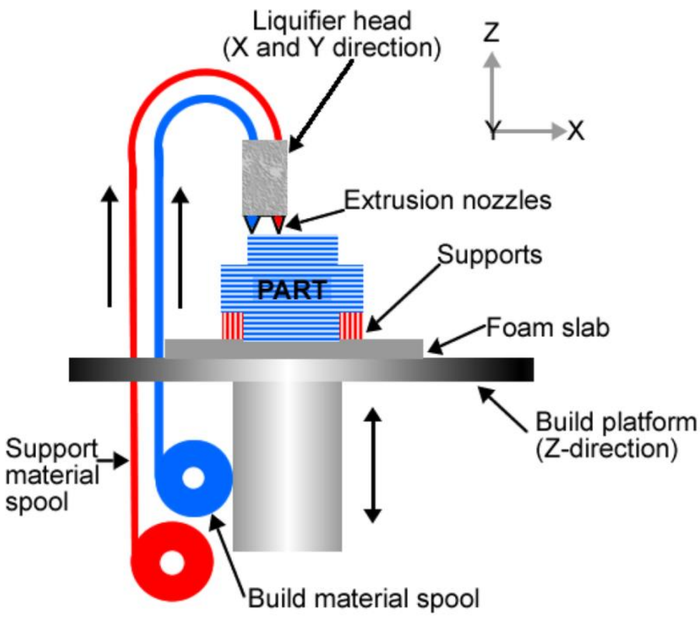


Fig. 2 FDM Process Flow [6]

Due to wide range of availability of material FDM can produce functional parts for various industrial applications including aerospace, automobile and medical sectors. BMW and Bentley Motors use FDM process to produce their automobile components which reduces their build time and cost up to 50 percentages compare to conventional CNC machining process.A carrier rack prototype build by FDM process is shown in Fig. 3.

Fig. 3 The prototype carrier rack [7]

1.2.1.2 Stereolithography (SLA)

Stereolithography (SLA) is the first fully commercialized AM process introduced in mid 1980s by 3D systems, California, USA. It fabricates part from a photo curable liquid resin that solidifies when sufficiently exposed to a laser beam that scans across the surface of resin. Once irradiated, the resin undergoes a chemical reaction to become solid called photo polymerization [8]. In SLA, there is a platform in a vat of liquid, photocurable polymer, i.e. epoxy or acrylate resin. After each cross-section is traced, the platform moves down an incremental amount and the laser cures the next cross-section. This process continues until the part is complete.

At initial days, SLA was mainly used as a prototyping tool; however, several companies are now using SLA for production manufacturing. For example, Siemens, Phonak, Widex and other hearing aid manufacturers use SLA machines to produce hearing aid shell [9]. Align Technology uses SLA to fabricate molds for producing customized clear braces (Invisalign®) [10]. Fig. 4 shows examples of products manufactured using SLA machines.

Fig. 4 Siemens hearing aid manufactured using SLA process [9]

1.2.1.3 Selective Laser Sintering (SLS)

Selective laser sintering (SLS) uses a high-powered laser to selectively heat the grains of a powder to their melting temperature and then fuse them to form the cross-section of a part. During the SLS process, a roller spreads a thin layer of powder across the build platform. The SLS machine preheats the powder in the build platform to a temperature just below its melting point in order to minimize the laser power requirement. A CO_2 laser scans the cross-section area generated from the 3D CAD model of the part and selectively fuses the powder. After each cross-section is scanned, the build platform is lowered by one layer, a new layer of powder is applied on top of the previous layer, and the fusion process is repeated. These steps are repeated until the part is complete [11].

SLS can build both plastic and metal components that include polymers such as nylons and polystyrene and metals i.e. steel and titanium. Boeing and its supplier uses laser sintering to build over 80 separate components for their F-18 military jet [12]. An example of an SLS-manufactured exhaust manifold is shown in Fig. 5.

Fig. 5 Propeller made by SLS [13]

1.2.1.4 Advantages of Additive Manufacturing

Additive manufacturing has the potential to vastly accelerate innovation, compress supply chains, minimize materials and energy usage, and reduce waste. It has several key advantages over traditional material removal methods. These include:

- **Lower energy intensity**: These techniques save energy by eliminating production steps, using substantially less material, enabling reuse of by-products, and producing lighter products.
- **Less waste:** Building objects up layer by layer, instead of traditional machining processes that cut away material can reduce material needs and costs by up to 90%.
- **Agility:** Additive techniques enable rapid response to markets and create new production options outside of factories, such as mobile units that can be placed near the source of local materials. Spare parts can be produced on demand, reducing or eliminating the need for stockpiles and complex supply chains.
- **Customizability:** Additive manufacturing process allows customization of parts without modification of the manufacturing process and toolings. Only the CAD model of a part needs to be altered for the customization. Later modified part can be printed without disturbing the complete manufacturing process.

1.2.1.5 Limitations of Additive Manufacturing

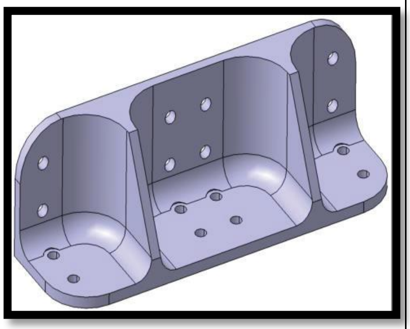
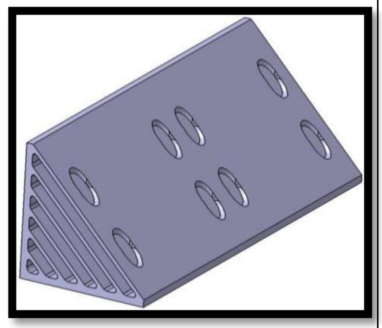
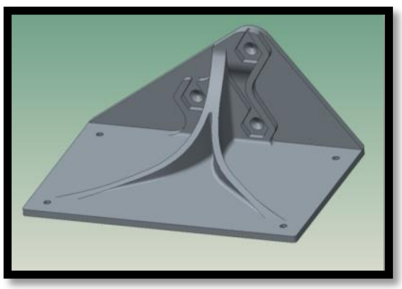
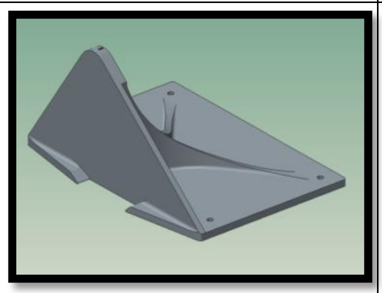
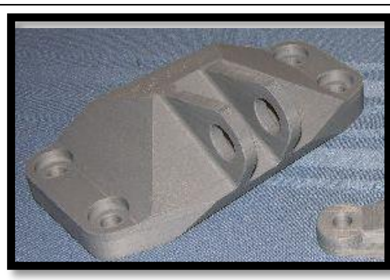
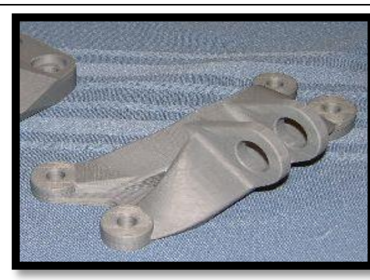
Though AM successful meet the demands of many industrial users, however, there are some disadvantages when using this technology, mainly in terms of build speed, accuracy, and material density.

- **High production costs:** High-precision AM machines are still expensive at around \$300,000 to \$1.5 million, and materials can cost \$100 to \$150 per pound. Therefore, in some cases, this technology is not suggested for mass production purpose.
- **Requires post-processing:** The surface finish and dimensional accuracy may be lower quality than other manufacturing methods. Hence post-processing may be needed to improve the part quality.
- **Poor mechanical properties**: Layering and multiple interfaces can cause defects in the product
- **Considerable effort required for application design and for setting process parameters –** Complex set of around 180 materials, process and other parameters need to review for production of quality products.

1.2.2 Design for Additive Manufacturing (DFAM)

Design for manufacturing (DFM) has typically meant that designers should tailor their designs to eliminate manufacturing difficulties and minimize manufacturing, assembly, and logistics costs. The great potential of AM removes nearly all limits in the manufacturing of parts. However, because of the enormous freedom conferred by AM, the challenge of AM is not the manufacturing of the part itself, but the design of component. Traditionally, the design methods are mainly focused on mold-based production systems, they do not allow designers to benefit from the opportunities AM has to offer. However, in the DFM based workflow, the designer develops a customizable design by considering unique capabilities of AM process that enables improvement in product performance and lowers manufacturing costs. Table 1 shows some customized parts that are re-designed by design engineers to fully exploit the geometric freedom of AM.

Table 1 DFAM Examples

No.	Designer	Initial Design	Final Design	Remarks
1	Vayre et al.			The re-designed part proved to be lighter compare to its initial model. [14]
2	Thomas Wood			In the final design, holes are removed and the later drilled manually to save support material. [15]
3	EADS Innovation Works			The optimized Airbus A320 allowed to reduce raw material consumption by 75%.[16]
4	GE Aviation			The final design made plane engine 1,000 pounds lighter [17]

In some design problems, where aesthetics and ergonomic is main concern of prototyping, fabricating hollow prototype instead of solid, is considered as a good design practice to save expensive build material (Fig. 6).

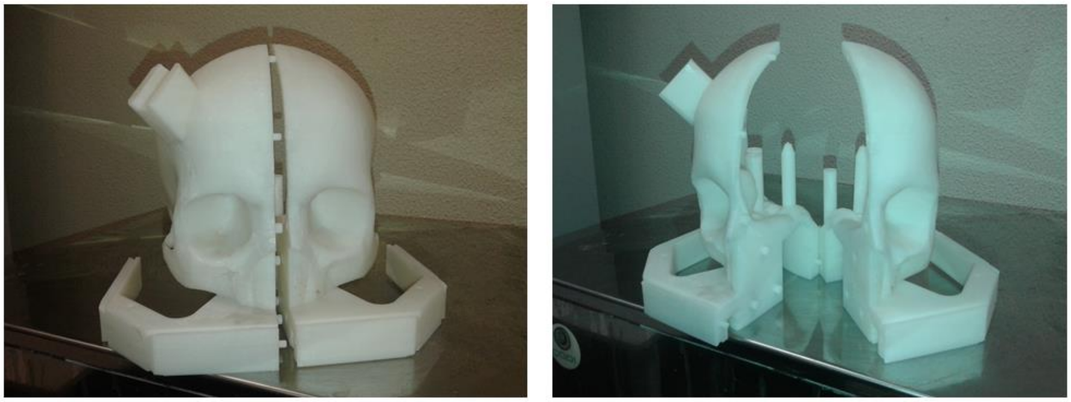


Fig. 6 Designed hollow prototype for material saving

Also while designing part in FDM, self-supporting feature should be considered for saving soluble support material (Fig. 7).This self-supporting angle varies from machine to machine and material used for building the part.

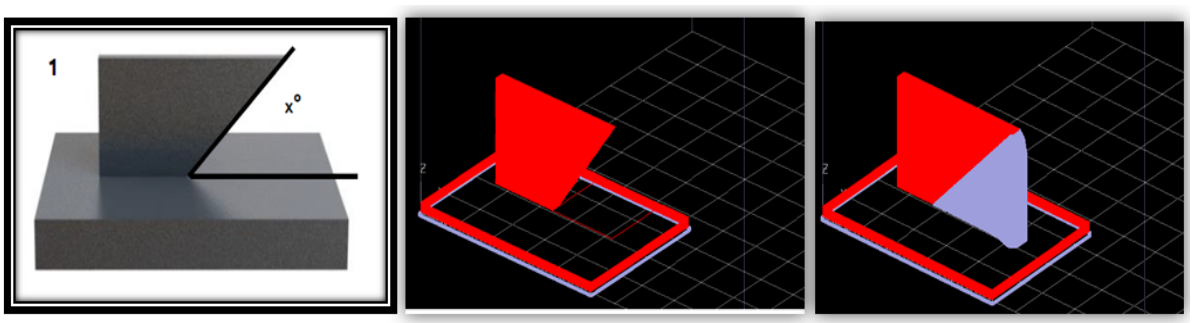


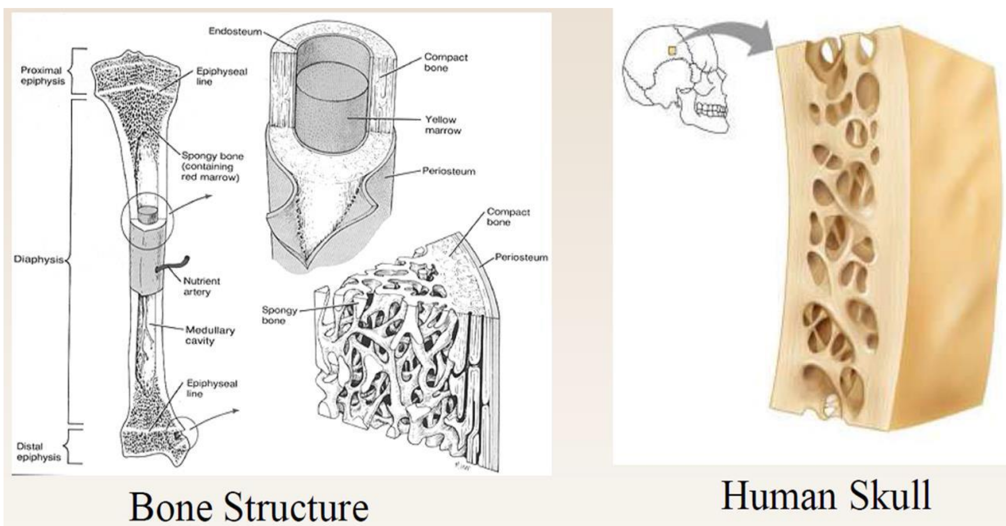
Fig. 7 Self Supporting design in FDM

The aforementioned design examples reflect that AM can increase the sustainability of products on environmental and economic level by producing;

- **Less material waste:** AM produces less waste compare to conventional material removal manufacturing process such as milling.
- **Lightweight products:** The shape complexity feature allows AM to produce net shape material of any size, thus making light weight products (Table 1).
- **Material complexity parts:** Material can be processed one-point, or one layer, at a time, enabling the manufacture of parts with complex material compositions and designed property gradients.

- **On-demand products:** Products can be produced in short time after the moment the user requests it, instead of in advance production. This leads to less overproduction and consequently to less destruction of unsold products.

Though these light weight prototypes can save expensive build material to a great extent, they are lack in mechanical strength and hence remembered as unfit for load bearing applications. In contrast, a full solid model may withstand the applied load, but at the same time it consumes more material for this. Hence a perfect tradeoff between material consumption and load bearing strength needs to be developed to further enhance the application of AM process. Designing cellular materials have been found to be best alternative in this perspective, since a key advantage offered by cellular materials is high strength accompanied by a relatively low mass (Fig. 8).



*"When modern man builds large load-bearing structures, he uses dense solids; steel, concrete, glass. When nature does the same, she generally uses **cellular materials**; wood, bone, coral."*

There must be a reason for it.

Fig. 8 Motivation for cellular structure

1.2.3 Cellular Structures

Cellular structures with tailored mechanical properties are highly demanded in many areas of industrial applications such as thermal insulation, packaging, light weight structure, bone scaffolds etc. In recent years, AM processes have been found to be a promising technology, capable of producing such products with precise porosity and pore sizes. Advantages of these structures compare to their solid-body counterparts include good energy absorption characteristics, strong thermal and acoustic insulation properties, and, most importantly, a high strength over the low mass consumption. Some examples of cellular structures are foam, honeycomb, and lattice, etc. They are displayed in Fig. 9 [18, 19, and 20]

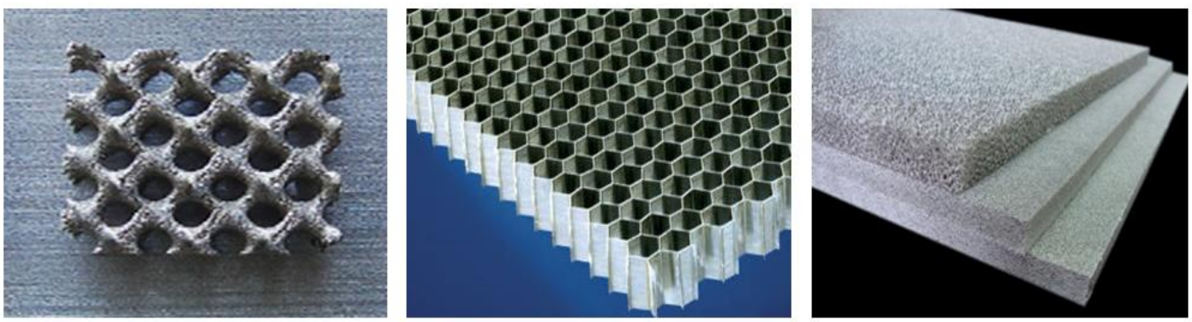


Fig. 9 Cellular lattice structure (left); hexagonal honeycomb (middle); aluminum foam (right)

These cellular structures are classified into two categories: those produced using stochastic processes (e.g. foaming) and those designed using deterministic processes (e.g. designed lattice materials). Deshpande et al. point out that foam's strength scales roughly to $\rho^{1.5}$, while the strength of lattice material scales to ρ, where ρ is the volumetric density of the material [21]. Therefore, a lattice material with a $\rho = 0.1$ is about three times stronger than a foam with the same volumetric density. The high difference in strength is attributed to the fact that foam deforms by cell wall bending while lattice elements stretch and compress [22]. Fig. 10 shows the detailed classification of these structures as per to their inbuilt topology [23].

This research presents a design methodology that enables designers to take advantage of the shape complexity capability of AM processes. Specifically, we are focused on the design of periodic cellular structures for AM process.

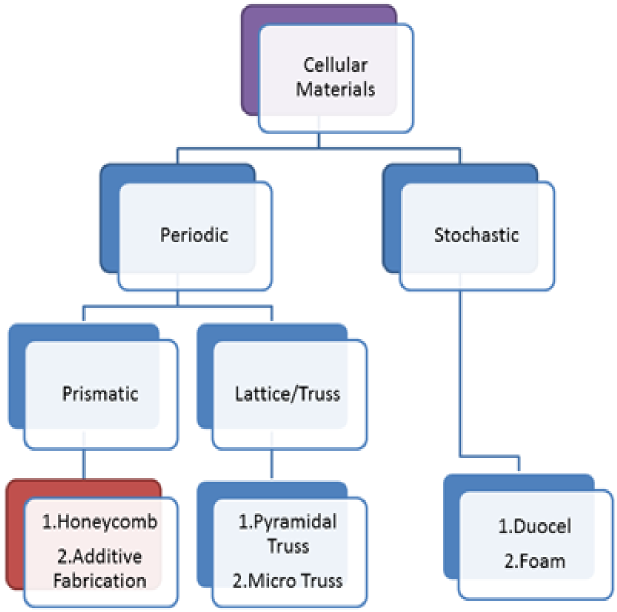


Fig. 10 Cellular structure classifications

1.3 Motivation

1.3.1 Design of Hexagonal Honeycomb Lattice Structures

Honeycomb is a two-dimensional periodic cellular material that is relatively strong and stiff along the normal to the microstructure but compliant and weak in-plane. This material is highly suitable for any weight-loading applications, particularly in the automobile and aerospace industries, which desire components with high strength-to-weight ratio. However, designing honeycomb structure using conventional machining process is a difficult and time consuming task. In this regard, AM seems to be an alternative solution due to it's design freedom capability and thus, it will be interesting to explore the ability of AM process, especially FDM, towards designing hexagonal honeycomb structures for any load bearing application. The motivation behind designing hexagonal honeycomb structure is it's self-supporting nature which in turn reduces support material volume in FDM process. Apart, it will save lots of expensive build material by putting the material where there is a need of it.

The biggest challenge associated with hexagonal honeycomb is not manufacturing of the part itself, rather the design of component. Although several approaches have been developed in the literature, there are significant limitations exist with these methods. These issues must be resolved in order for the method to be more effective and versatile.

1.4 Goals

The main goal of this thesis is to improve the material distribution inside a functional part body that lowers material consumption without sacrificing it's need. There are several subtasks, found through exhaustive literature review (in chapter 2), need to be completed in order to achieve this goal. They are as follows:

- To design the hexagonal honeycomb structure with the help of CAD tools.
- To automate the complete process for minimizing CAD complexity, and processing time.
- To investigate microstructure and mechanical properties for their performance improvement.
- To test this designed cellular structure for an industrial application using FDM process.

1.5 Organization of thesis

Six chapters presented in this thesis are organized as follows:

Chapter 1: Introduction, Background and Motivation

This chapter introduces the concept of AM including basic applications and importance of design for AM. This chapter also provides the justification and need for present research work.

Chapter 2: Literature survey

The purpose of this chapter is to review related literature so as to provide background information on the issues to be considered in the thesis and emphasize the relevance of the present study. Literature review provides a summary of the ground work available in the broad area of AM, designing of cellular solids, microstructure and mechanical characterization, and DFAM guidelines.

Chapter 3: Design Method

In this chapter, our proposed design method is presented that will resolve the technical limitations of CAD implementations via CATIA automation. This design method is able to efficiently design cellular structures (hexagonal honeycomb) internally inside any complex shape part which is confirmed in next chapter.

Chapter 4: Microstructure and Mechanical Characterization

This chapter investigates the microstructure and mechanical properties of hexagonal honeycomb cellular structures thoroughly with a wide range of cell size (5–15%) and wall thickness (1&3 mm). Manufacturability and performance of our designed honeycomb structure is also evaluated here via FDM process.

Chapter 5: Design Example

This chapter considers an industrial example, known as, resin transfer moulding (RTM) to validate our design methodology. RTM mould is redesigned to save expensive build material and time, compare to a solid FDM mould. The comparative analysis along with necessary trade-offs are reported in following chapter.

Chapter 7: Executive summary and conclusions

This chapter presents the summary of the results, recommendations and scope for future work in the direction of studies on effect of uncertainty on supply chain performance. It also discusses the specific contributions made in this research work and the limitations there in. This chapter concludes the work covered in the thesis with implications of the findings and general discussions on the area of research.

1.5 Summary

This particular chapter is dedicated towards the collection and sharing of information, technical knowhow of operation of AM and discusses various recent advances related to it. The primary motivation behind this chapter is to make the readers know about the fundamentals of AM and it’s basic design guidelines.

The chapter starts with explaining the AM processes along with its different field of application like automobile, aerospace, medical, and concept modeling. The importance of DFAM is also described along with the different types design examples that plays a vital role in the widespread application of this technology. Going through these discussions, the readers can make themselves aware of the best design practices to be adopted while employing AM for fabrication of the functional products.

Chapter 2

LITERATURE SURVEY

2.1 Overview

In this chapter, a literature survey of relevant research is presented. Having the concept of AM was introduced in mid-1980s; literature survey begins with papers published after 1990 with maximum attention paid to last ten years. The search was restricted on those articles for which full text was available. The literature is classified into an assortment of sections dealing with specific issues associated with AM as illustrated in Figure 11. Figure 12 provides the breakdown of the number of citations by research classification. Next sections provide brief discussion on these issues. Finally, chapter is concluded by summarizing the advancement taken place in AM technology and possible literature gap so that relevance of the present study can be emphasized.

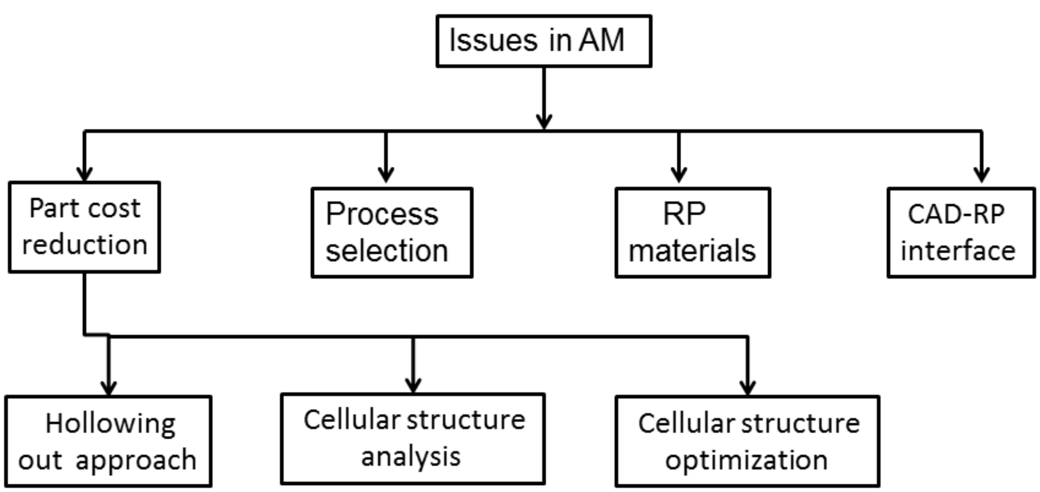


Fig. 11 Research issues in AM

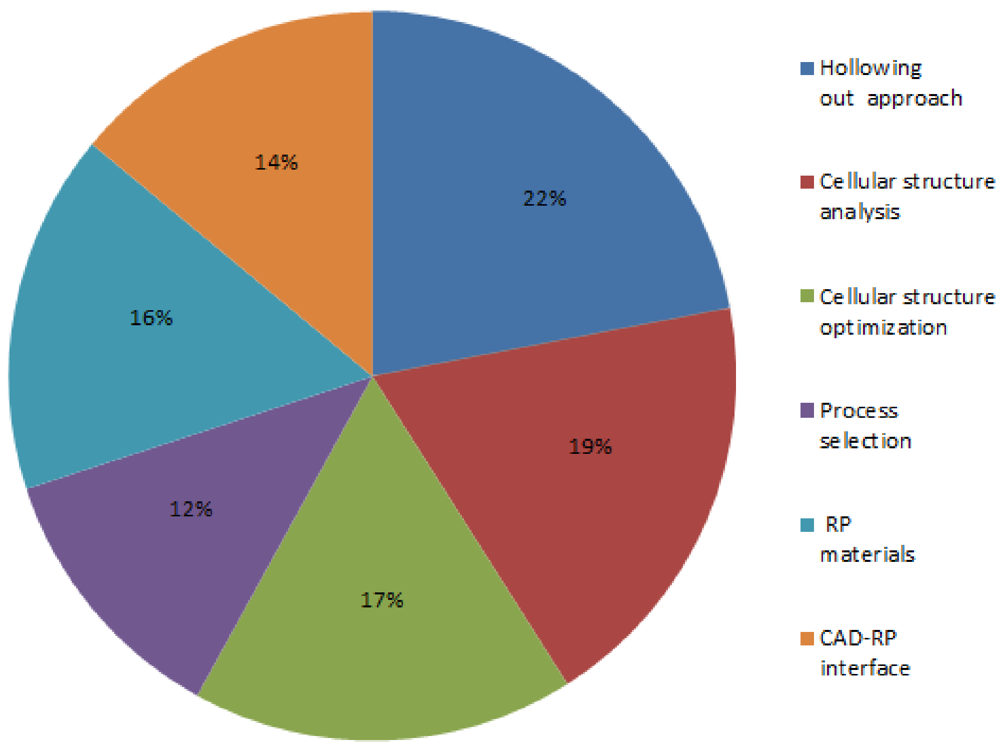


Fig. 12 Percentage of paper surveyed

2.2 Hollowing Approaches

Many studies are identified with respect to design improvement of AM parts. Out of all, important and relevant research works are presented in Table 2. It summarizes the design approach: hollowing a part with uniform wall thickness, adopted by several researchers to save expensive build material while designing a part for aesthetic and ergonomic analysis.

Table 2 Summary of literature review

Sl. No.	Author(s)	Title	Summary of research	Remarks
1.	Yu and Li (1994)	Speeding up rapid prototyping by offset	This paper proposes to use solid offset to cut down the solid volume to be built. The background theory for obtaining the reduced-volume solid is negatively offsetting the CSG	The approach is applicable to solids defined by constructive solid geometry (CSG)

			model.[24]	
2.	Ganesan and Fadel(1994)	Hollowing rapid prototyping parts using offsetting techniques	A simple effective method is presented here for creating (outside of the solid modeler) hollow CAD models of the object using offsetting techniques.[25]	This method is not suitable for creating hollow parts that have varying surface normals
3.	Koc and Lee (2002)	Non-uniform offsetting and hollowing objects by using biarcs fitting for rapid prototyping processes	This paper presents a new method of using non-uniform offsetting and biarcs fitting to hollow out solid objects or thick walls to speed up the part building processes on rapid prototyping (RP) systems.[26]	Offset STL model contains some triangular facets with overlaps and inconsistent orientations
4.	Qu and stucker (2003)	A 3D surface offset method for STL-format models	This paper presents a new 3D offset method for modifying CAD model data in the STL format. In this method, vertices, instead of facets, are offset. The magnitude and direction of each vertex offset is calculated using the weighted sum of the normals of the facets that are connected to each vertex.[27]	It works well for small offset values.
5.	Sang C. Park (2004)	Hollowing objects with uniform wall thickness	This paper proposes a new algorithm that computes internal contours without computing the offset model. The proposed algorithm is efficient and relatively easy to implement, because it employs well-known 2D geometric algorithms, such as planar curve offsetting and tracing innermost curves.[28]	The proposed algorithm is efficient and relatively easy to implement, because it employs well-known 2D geometric algorithms, such as planar curve offsetting and tracing innermost curves.
6.	Zhengyu et al. (2004)	A new hollowing process for rapid prototype models	In this paper a new method of hollowing rapid prototype models based on STL models and their cross-sectional contours is	This method has been verified by practical case studies, and it is proved that this

			presented to meet the demands of hollowed prototypes in casting and rapid prototype manufacturing. Offsetting along the Z-axis and cross sectional contour offsetting are employed to perform the hollowing operation.[29]	simplified hollowing operation can reduce the prototype build time and cost.

2.3 Cellular Structure Analysis

The main task involved in the analysis of cellular structures is to predict the mechanical properties and model their performance accurately. Several methods have been developed to analyze various cellular structures. For instance, Ashby et al. has conducted extensive research in the area of metal foams [22]. Murr et al. [30] measured the stiffness of Ti–6Al–4V open cellular foams fabricated by electron beam melting (EBM). Results are found to be in good agreement with the Gibson–Ashby model for open cellular foam materials Wang and McDowell have performed a comprehensive review of analytical modeling, mechanics, and characteristics of various metal honeycombs [31]. Campanelli and his co-authors [32] investigated compressive property of Ti6Al4V pillar textile unit cell made by selective laser melting. Assuming, struts in a lattice structure only undergo axial loading and that joints are pin-pin joints, Wallach and Gibson analyze sheets of lattices under axial loading conditions [33].Compared to experimental analysis, their framework reported errors ranging from between 3% and 27%. Chiras et al. extended this assumption to analyze similar structures undergoing bending and shear loading [34]. Johnson et al. provided a more comprehensive analytical model of the truss structure by considering each strut as a beam experiencing axial, bending, shearing, and torsion effects. He analyzed the octet-truss structure inside finite-element environment using a unit-truss model that consists of a node and set of half-struts connecting to the node [35]. Wang et al. also have applied this unit-truss method to design and represent lattice structure [36]. Considering a BCC-Z unit cell Ravari et al. [37] predicted the variation in struts' diameter of on the elastic modulus as well as collapse stress of CLS using both beam and solid finite element models. Chang et al. [38] proposed and deployed a new design approach called size matching and scaling (SMS) method for designing mesoscale lattice structures. Later this was improved in terms of unit cell types for generating conformal lattice structures [39]. Conformal lattice structures are the one among meso scale cellular structure that conformed to the shape of a part’s surface and can be used to stiffen or strengthen a complex part where standard lattice fails to fulfill it.

2.4 Cellular Structure Design and Optimization

2.4.1 Size, Shape, and Topology Optimization

In order to understand optimization of structures, the definitions of three categories of structural optimization are explained below (Fig. 13). Literature reveals that the optimization of part geometry and topology of the structural lay-out has a great impact on the performance of the structures [40].

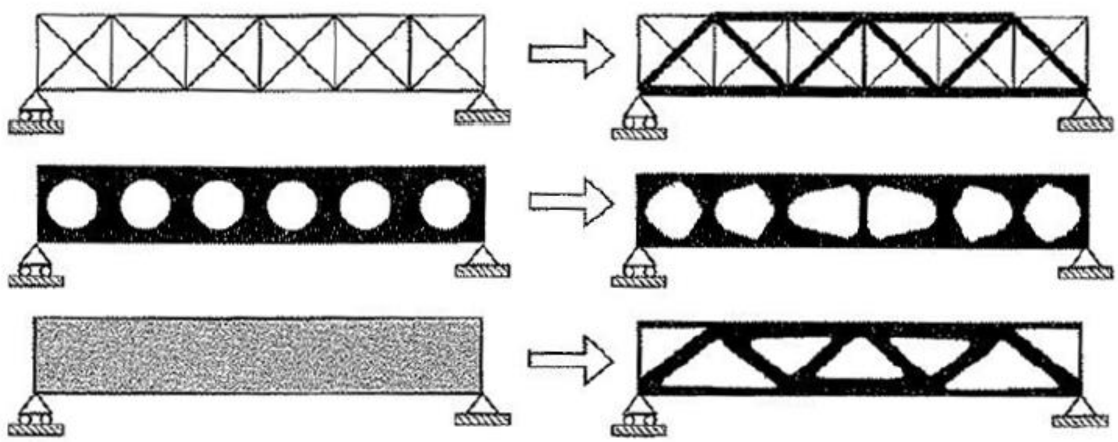


Fig. 13 Size (top), shape (middle), and topology (bottom) optimization [40]

A typical size optimization involves finding the optimal cross-sectional area of each strut in a truss structure [41]. Shape optimization computes the optimal form that defined by the boundary curves or boundary surfaces of the body [42, 43]. The process may involve moving nodes to change the shape of the structure; however, the element-node connectivity remains intact. According to Rozvany, topology optimization can be defined as determining the optimal connective sequences of members or elements in a structure. It consists of both size and shape optimization and has been used most frequently by design engineers to optimize their part structures for AM application (Section 1.2.2)

The topology optimization techniques used by the design are based on one of two approaches: the homogenization (continuum) approach and the ground (discrete) truss approach [44]. By using some continuous variables such as cross-sectional area, void sizes, these two approaches transform the discrete problem into a continuous one. The details of these two approaches are discussed in [45] [46].

2.4.2 Multivariable Optimization

Though structural optimization approach is used for the design, there is always a need for actual optimization routine. There are many different optimization algorithms depending on the applications such as mathematical programming techniques, stochastic process techniques, and statistical methods [47]. According to Rozvany and Zhou, these algorithms fall in two categories: direct methods and indirect method ([48], [49]). Direct methods (mathematical programming) consist of iteratively calculating the value of the objective function, its gradient with respect to all the design variables, and a change of design variables resulting in cost reduction until the local minimum of the objective function is found [50]. These methods are very robust, however, the calculation of gradients can be time-taking process, and sometimes can only optimize a limited number of design variables. On the other hand, indirect methods, such as optimality criterion, attempt to satisfy some design criteria of the structure instead of optimizing the main objective function. In many cases, such as uniform stresses, it has been found that direct method provides the same solutions as that of indirect methods [51]. Chu et al. compared the performance of three methods namely, Particle Swam Optimization (PSO), Levenberg-Marquardt (LM) and Active-set Programming while designing octet lattice cellular structures to achieve desired strength and stiffness [52]. Results show that LM is more efficient algorithms for this class of problems.

2.5 Process selection

Selection of an appropriate process requires addressing to various criteria such as cost, part quality, part properties, build envelope, build time (speed) and other concerns suiting to a particular situation. A number of studies have been carried out in this direction, predominantly concerning with the development of decision support systems for assisting AM users in selecting the most appropriate AM process.

Recent efforts in selection of AM system have been directed to the development of computer based selector programs [53, 54, 55]. In this direction, analytic hierarchy process (AHP) has proved to be an effective tool that best fits the end user‟s needs [56, 57]. Industrial Research Institute, Swinburne (IRIS) have proposed a rule based RP system selector that uses selection criteria such as the price of the machine, accuracy, surface finish, build envelope, type of material and building speed. The database includes full specifications for each RP machine which is displayed when the program recommends the specific RP machine [58, 59]. The major limitation of the program is that it cannot take care of conditional statements. Byun and Lee [60] used a modified technique of order preference by a similarity to ideal solution (TOPSIS), a multi attribute decision making (MADM) approach, for ranking RP systems by means of ratings with respect to multiple attributes. The major attributes used for RP process selection include accuracy, surface roughness, strength, elongation, build time and cost of the part. Similarly, panda et al. [61] used integrated AHP and TOPSIS to rank RP process under dimensional accuracy, surface quality, part cost, build time and material properties attributes. A method integrating the expert system and fuzzy synthetic evaluation (FSE) is proposed by Lan et al. [62] to select the most appropriate RP process according to users‟ specific requirements. Rao and Padmanabhan presents a methodology for selection of a RP process using graph theory and matrix approach [63]. A rapid prototyping process selection index is proposed to rank the RP processes for producing a given product or part. Subburaj et al. [64] presented a computer aided rapid tooling (RT) process selection and manufacturability evaluation methodology that not only helps in RT process selection but also facilitates identifying difficult-to-manufacture features of a part. Jin et al. [65] presents an adaptive approach to improve the process planning of Rapid Prototyping/ Manufacturing (RP/M) for biomedical models. Five complex biomedical models are used to verify and demonstrate the improved performance of the approach in terms of processing effectiveness and geometrical accuracy.

2.6 RP/AM Materials

AM is capable of using solid, liquid, and powder as a base material but the choice of material within each category is limited by the constraint offered by AM process itself. With the advancement in material technology and RP machines, lot of activities in materials development has been observed over the past years. For example, Z Corporation introduced zp 140, a high-performance material, for its 3D printing process. The new powder material is engineered for simple, fast, and easy post processing [66]. In comparison to traditional powder systems used for 3D printing, polymers like zinc-poly acrylic acid has shown better options particularly in terms of mechanical strength [67]. A new high performance thermoplastic composite involving thermo tropic liquid crystalline polymer (TLCP) fiber is developed for FDM system to fabricate prototype parts. The tensile modulus and strength of this material is approximately four times those of ABS [68].

Lejeune et al. [69] used lead zirconate titnate and titanium dioxide ceramic suspension respectively for fabricating different kinds of micro pillar array structures. A few authors have used industrial material such as such as 316 and 304 stainless steel, nickel based super alloys such as Inconel 625, 690, and 718, H13 tool steel, tungsten, TI-6AL-4V titanium alloy, and nickel aluminides for prototype (cellular) production using some new, advanced AM machines (direct metal laser sintering (DMLS), laser engineered net shaping (LENS), direct metal deposition (DMD), ultrasonic consolidation (UC), selective laser melting (SLM)) [70,71,72]. Literature reveals that these new machines show great potential with higher degree of precision and less inner stress.

2.7 CAD-RP interface

RP process starts with the creation of solid or surface model of a part to be fabricated using any suitable CAD software. As current RP machines are not able to read the model data in its native CAD software format; so it has to be converted into other format which is accepted by RP machine. 3D Systems Inc., first set the de facto file-format standard for the RP industry in 1988 known as STL (Stereo-lithography) format. The STL format is a polyhedral representation of the part with triangular facets. It is generated from a precise CAD model using a process known as tessellation which generates triangles to approximate the CAD model.

Though STL format is accepted over all AM machines, it has few limitations which result poor surface finish and dimensional inaccurate parts. Other than this problem, STL format has inherent drawback like redundancy of information i.e. each vertex of a triangular facet is recorded at least four times. This brings extra computational memory occupation and time consumption. Therefore, in the last few years, many research efforts have been dedicated to determine better interface between CAD and RP technology [73, 74, 75]. To overcome the limitations of STL formats, some researchers even suggested the direct integration of CAD models with RP machines to generate geometric data for rapid prototyping. These methods generate slicing data directly from the original CAD model without using the STL format. There are many practical situations where actual CAD model of part is not available or difficult to construct. In these situations, the physical model or sample must be reverse engineered to create or refine the CAD model. Then this CAD can be given as input to RP machine fort direct prototyping without losing any information. To use CAD model as a direct input, instead of STL, several researchers have developed CAD based slicing algorithm for slicing down the CAD models into several layers [76, 77, 78, 79, 80, 81, 82].The major advantage of using CAD models over STL format is that, it eliminates the tessellation error encountered in the part which will enhance part quality in terms of surface finish and dimensional accuracy.

2.8 Summary

The aforementioned literature review concludes that much work has been done in the last decade related to the generation of truss type cellular structures. As per authors knowledge FDM is least used compare to SLA and SLS for generating these structures. This may be because of high grade material availability with SLA and SLS system. Both Computer-aided design (CAD) based geometrical modeling and mathematical modeling are addressed by many researchers for designing these cellular structures [83], In addition, recently developed SMS and Relative density methods by Rosen and his co-authors have promising performance for generating variety of cellular structures [84]. Regarding CAD modeling, a few authors stated that this is not a suitable platform for designing these complex structures; since it involves lot of design variable and takes lots of memory and time for processing operation. However, this problem can be tackled with the help of current advanced CAD toolbox and automation via macro programming. Therefore, in this research, a CAD based approach for generating cellular lattice structure (Hexagonal Honeycomb) is proposed and also evaluated for a real world load bearing application (Resin Transfer Molding). Considering the system (here FDM) potential/limitation in terms of material availability, dimension accuracy and the highly significant support generation strategy, honeycomb pattern is designed in this work among the wide range of cellular structures.

Chapter 3

DESIGN METHOD

3.1 Overview

In this section, a CAD based design method will be presented. The method will resolve the technical limitations of previous CAD based approach by utilizing an advance CAD toolbox and automation. This design method will be able to efficiently design hexagonal honeycombs inside any complex shape part body without delay in file processing and human error. The methodology for generating honeycomb structures consists of two design phases (Fig. 12). Phase 1 is related to the hollowing process with uniform shell thickness, while phase 2 facilitates reinforcement of the honeycomb structure inside the hollow part body, generated in phase 1.

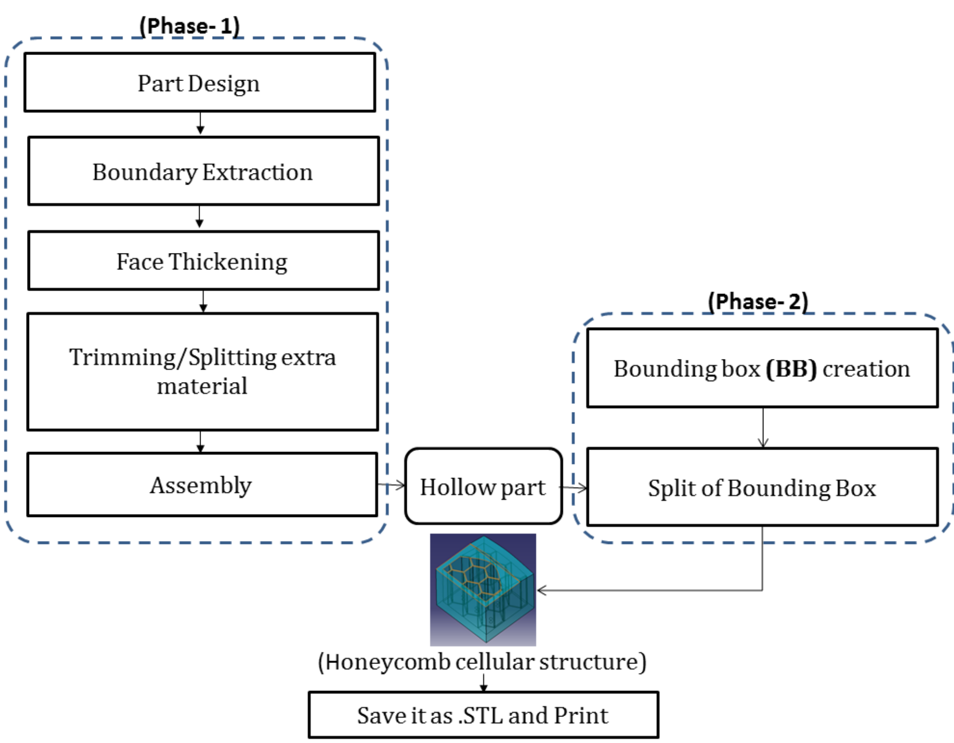


Fig. 14 Proposed Method

Following sections explain the steps in Fig. 14 with graphical illustrations for a clear understanding of the complete process. The process is implemented in the framework of a commercial CAD package, CATIA V5, used by most of design engineers for generating open porous structures. After part generation, the complete design methodology is automated using CATIA VB Script programming to reduce run time as well as the human effort.

3.2 Phase 1

3.2.1 Part Design

In the first step, a part is to be designed as per user requirements. Users can specify their requirements in terms of geometric features such as shape, size of the part along with different loading conditions (analytic feature) that are needed to perform stress analysis while designing cellular structures for it.

3.2.2 Boundary Extraction

Here, the boundary of part of the solid body is extracted into one or multiple faces with tangent continuity.Fig.15 represent a solid part and the extracted boundary with multiple surfaces is represented in Fig.16 as an exploded view.

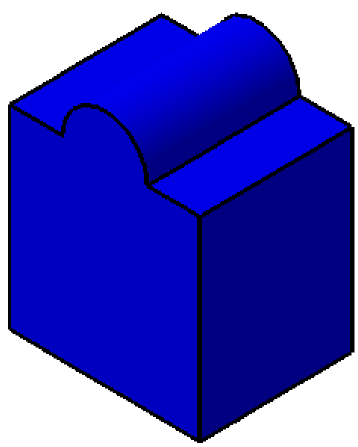


Fig.15 The 3D solid part

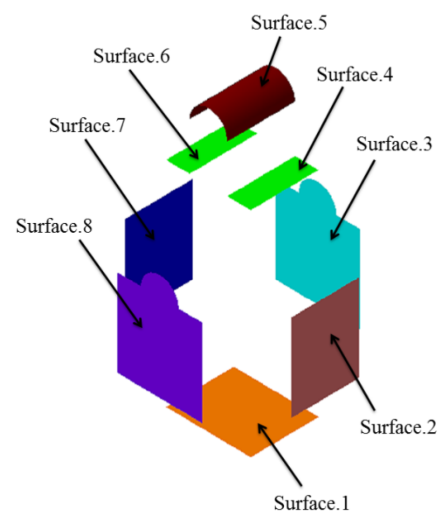


Fig.16 Exploded view of boundary surfaces

3.2.3 Face thickening

In this step, solid bodies are created by thickening each surface to a specified thickness normal to the surface towards material direction. Designers have the rights to change this value (thickness) as per their need for application. Fig.17 represents the surface normals towards the material direction for all surfaces (Surface8 is moved in the normal direction for clear representation). Fig.18 represents the thickened bodies (Surface8 and the respected thickened moved in the normal direction for clear representation).

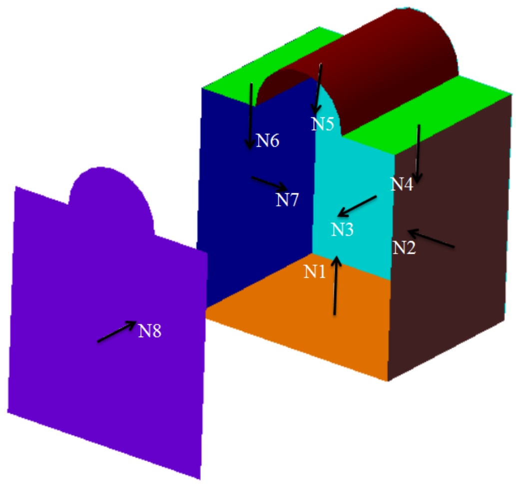


Fig.17 Direction of normal for each surface

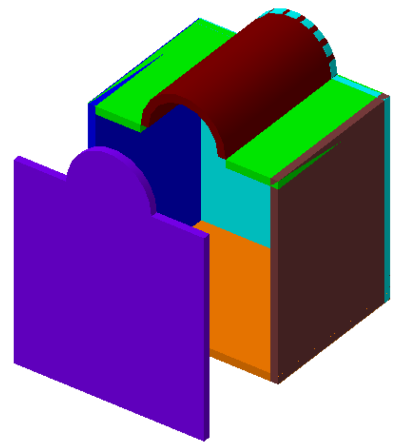


Fig.18 Thickened bodies

3.2.4 Trimming/adding the excess material

This step is not common to every solid part body, as it is a geometry dependent issue. In some case studies, it has been found that thickening surfaces result excess material or sometimes less material which is practically undesirable. Therefore if any thickened solid body crosses the boundary of the part, then the excess material will be trimmed with respect to the boundary. Fig.19 represents the excess material after thickening a face of the solid and the trimmed body with respect to the intersecting boundary surfaces is represented in Fig.20.

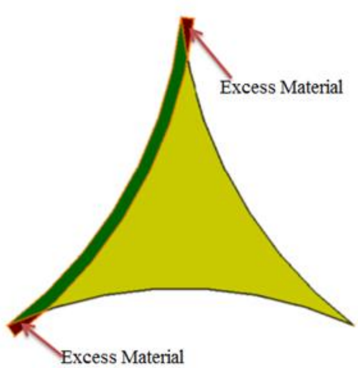


Fig.19 Excess material on thickened solid body

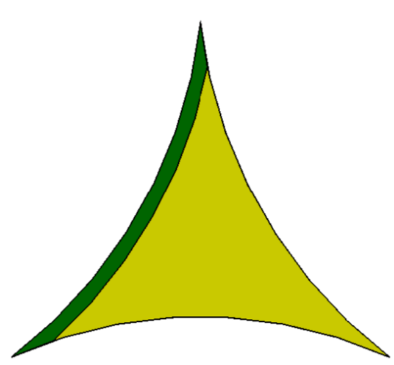


Fig.20 Trimmed body with respect to intersecting boundary surfaces

Similarly if there is a need of material, one of the surface can be extended up to the neighboring surface to maintain uniformity. Fig. 21 shows the gap (Need of material) when angle between the neighboring surfaces is convex. In order to generate a hollow uniform part body one of the surface should be extended in the opposite direction of material till it meets the other surface (Fig. 22).

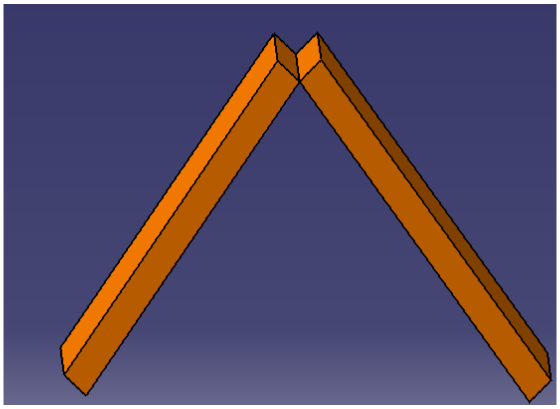


Fig.21 Gap in thickened solid body

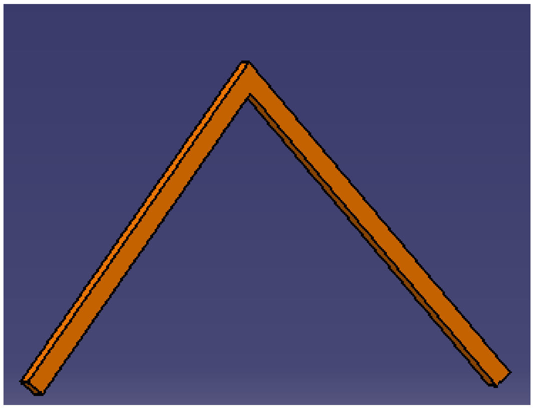


Fig.22 Extended thickened solid body

3.2.5 Assembly

All thickened bodies are assembled together to generate a part with internal hollow space without any deviation in the physical appearance. Fig.23 represents views of a 3D solid part, isometric view of the part, view from side and section cut to represent the internal configuration. Fig.24 represent the 3D hollow solid part created by using the proposed method, isometric view of the part, view from side with hidden lines and section cut to represent the internal configuration.

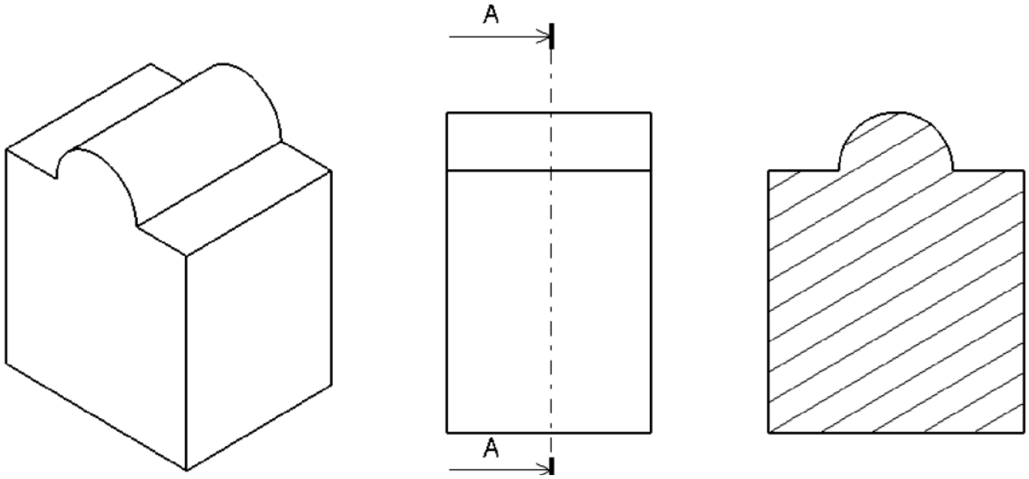


Fig.23 3D solid part views (Isometric view, View from side, Section Cut view)

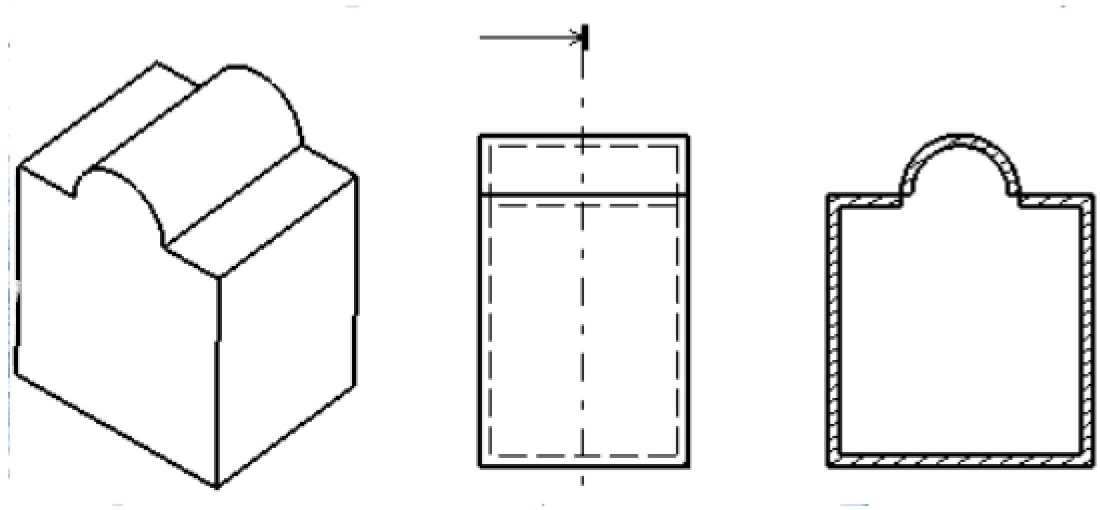


Fig.24 3D hollow solid part views (Isometric view, View from side, Section Cut view)

3.3 Phase 2

3.3.1 Bounding Box (BB) creation

Bounding box (BB), as the name refers; it is the minimum enclosing box surrounding the (hollow) part body. This BB creation is our preliminary step towards generating cellular structures inside any complex geometry part. Out of two types of BB (Fig. 25) minimum oriented BB is created with the help of advanced CAD tools for the hollow part shown in Fig. 26. The cell sizes of these honeycombs are controlled parametrically, in order to generate BB of different infill densities.

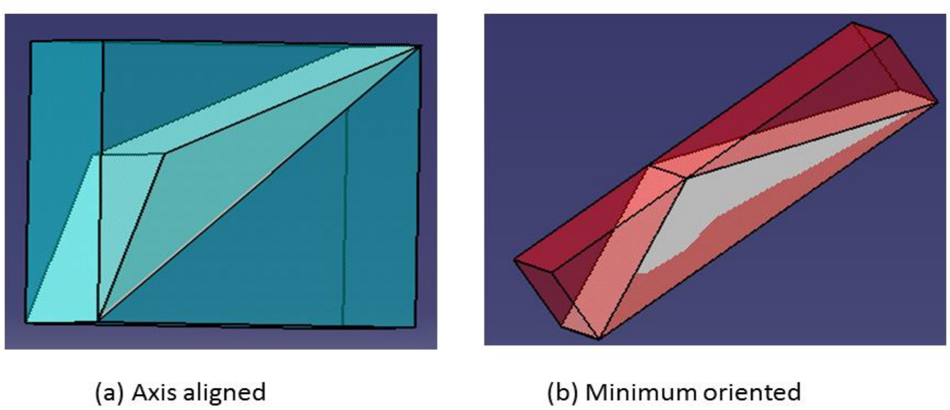


Fig. 25 Bounding box type

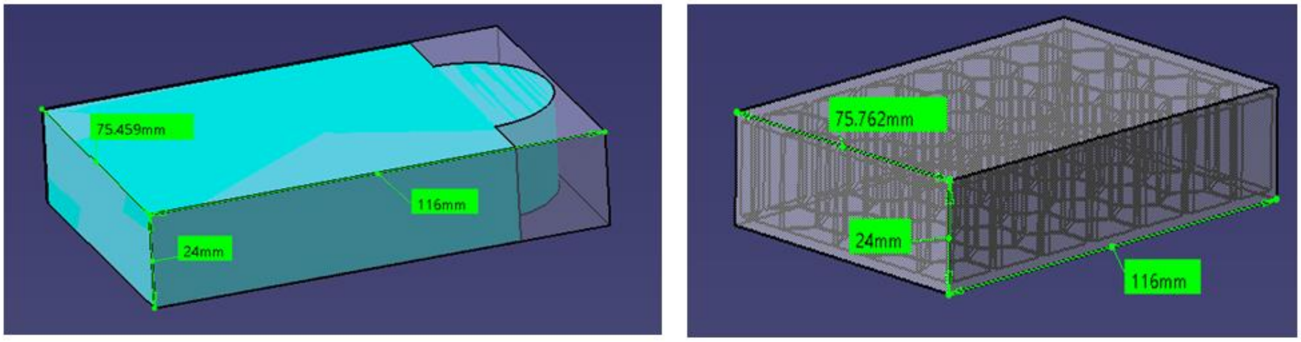
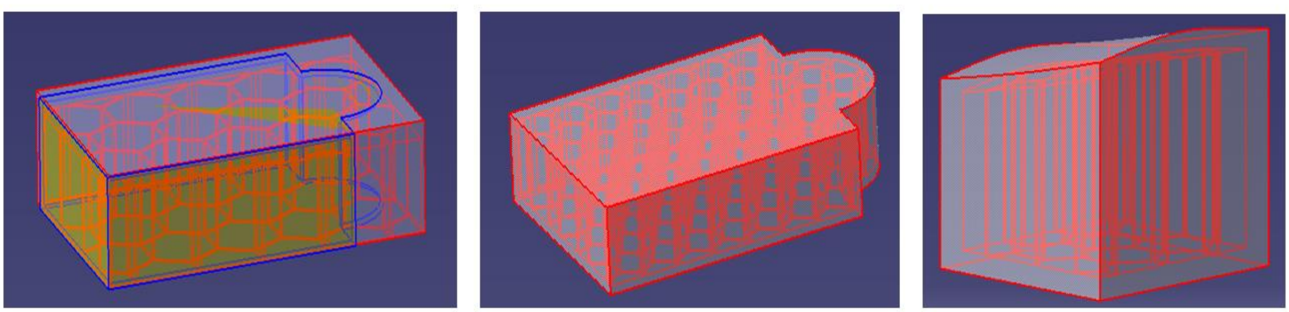


Fig.26 Bounding Box

3.3.2 Splitting of BB

This step produces internal honeycomb cellular structures for any complex shape part by splitting the BB with respect to internal contour (marked in blue) of the hollow part. Fig. 27(a) and (b) represents the splitting operation carried out to obtain internal honeycomb structure. In fig 27(c) (another part), the internal honeycomb structure is found to be a conformal one since it perfectly adapts to curve surface of the part body. This adaptive nature of the honeycomb structure is verified and discussed later in this paper by analyzing it's micrograph images.



(a) (b) (c)

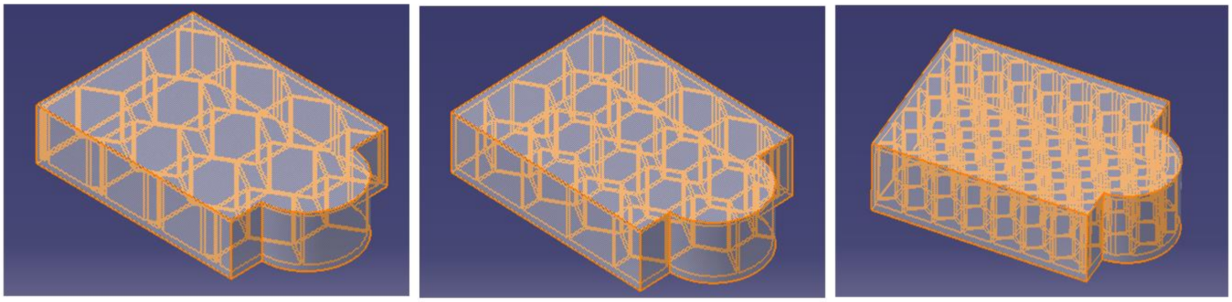
Fig.27 Splitting and Generating Hexagonal Honeycomb

4. Design Automation

Since the complete process seems to be lengthy and complicated, a macro program (using VB script) is written to minimize computational time and human errors while designing the part. The CATIA API (Application Program Interface) commands used in this program (for automation) are listed down in below Table 3. Users can run it by assigning some values to wall thickness and cell size for introducing honeycomb cellular structure inside any complex part bodies.

Table 3: CATIA Command List for automation

Operation	CATIA Command	CATIA API Command
Extract	Generative shape design > Operation > Extract	Set hybrid Shape Extract1 = hybridShapeFactory1.AddNewExtract(surface1)
Thicken	Part design > Surface > Thick surface	Set thickness1 = shapeFactory1.AddNewThickness(surface1, thickness value)
	Direction Selection	CATIA.ActiveDocument.Product. GetTechnologicalObject("Clashes")
Split	Generative shape design > Operation > Split	Set split1 = shapeFactory1.AddNewSplit(surface1, catPositiveSide/ catNegativeSide)
Assembly	Part body > Properties > Assembly	Set assemble1 = shapeFactory1.AddNewAssemble(body1)
Pad	Part design > Sketch based feature> Pad	Set pad1 = shapeFactory1.AddNewPad(sketch1, height)
Add	Part body > Properties > Add	Set add1 = shapeFactory1.AddNewAdd(body2)



(a) (b) (c)

Fig. 28 Hexagonal Honeycomb with infill (a) 25 (b) 30 (c) 35 percentage

Fig 28 shows, CAD models of three honeycomb cellular structures with different volume fractions such as 25%, 30%, 35% created using this program. *Volume fraction* is defined as the volume percentage of the solid material in the cellular structure. It is clear from this images that our proposed program is able to generate internal honeycomb structure for any complex part based on the values of wall thickness and cell size.

5. Summary

Design of cellular solid is often a difficult task using existing CAD packages due to the level of complexity associated with it. Therefore, in this chapter an efficient approach is presented to generate and design periodic cellular structures e.g. honeycomb with the help of advanced CAD tools. A commercial CAD package, CATIA V5 is used as the working environment to verify the robustness this proposed approach. Also to reduce computational time, whole program is automated using VB script programming and is validated for many complex shaped parts.

Using this program, designer can generate periodic cellular structures of varying density, without any difficulties. Though this design methodology is implemented inside CATIA framework, it can be also applied over other CAD packages with some modification in the command files. Users have to give input to the program by assigning values to wall thickness and cell size for successful generation of hexagonal honeycombs as per their need of applications.

Chapter 4

MICROSTRUCTURE AND MECHANICAL CHARACTERIZATION

4.1 Overview

Literature reveals that the mechanical properties of cellular solids are related to the properties of cell wall and cell geometry [85]. This makes it essential to understand the performance of cellular structures with the variation of these parameters for a successful industrial application. To achieve this, the present chapter investigates microstructure and mechanical properties of hexagonal honeycomb cellular structures with a wide range of cell size (5–15%) and wall thickness (1 &3 mm). The effects of cell size and wall thickness on the part density and compression properties (made by FDM) are evaluated. In addition, details of the part fabrication methodology and various tests that the samples are subjected are also explained in this part of the thesis.

4.2 Materials and Methods

4.2.1 Materials

The material used for test specimen fabrication is acrylonitrile butadiene styrene (ABS P400). ABS (chemical formula (($C_8H_8\cdot\ C_4H_6\cdot\ C_3H_3N)_n$) is a carbon chain copolymer and belongs to styrene ter-polymer chemical family. ABS is derived from acrylonitrile, butadiene, and styrene (Fig. 29). Acrylonitrile is a synthetic monomer produced from propylene and ammonia; butadiene is a petroleum hydrocarbon obtained from the C_4 fraction of steam cracking; styrene monomer is made by dehydrogenation of ethyl benzene - a hydrocarbon obtained in the reaction of ethylene and benzene. ABS is made by polymerizing styrene and acrylonitrile in the presence of poly-butadiene. The nitrile groups from neighbouring chains, being polar, attract each other and bind the chains together, making ABS stronger than pure polystyrene. Its three structural units provide a balance of properties with the acrylonitrile providing heat resistance, butadiene imparting good impact strength and the styrene gives the copolymer its rigidity [ ]. In the present study, the material supplied by the original equipment manufacturer is used.

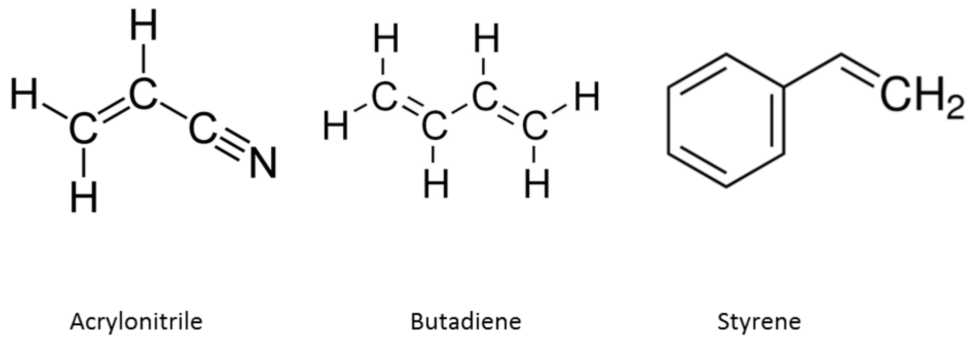


Fig. 29 Monomer in ABS

4.2.2 Specimen fabrication

The CAD model of hexagonal honeycomb cellular structures with different cell size and wall thickness are initially generated using our proposed design method, explained in chapter 3. Five different cell sizes such as 5mm, 7.5mm, 10mm, 12.5mm, 15mm and two different wall thicknesses of 1mm and 3mm are chosen for this purpose. The designed CAD model of the honeycomb structure with the cell size (5–15%) and wall thickness of 3.0 mm is shown in Fig. 30.

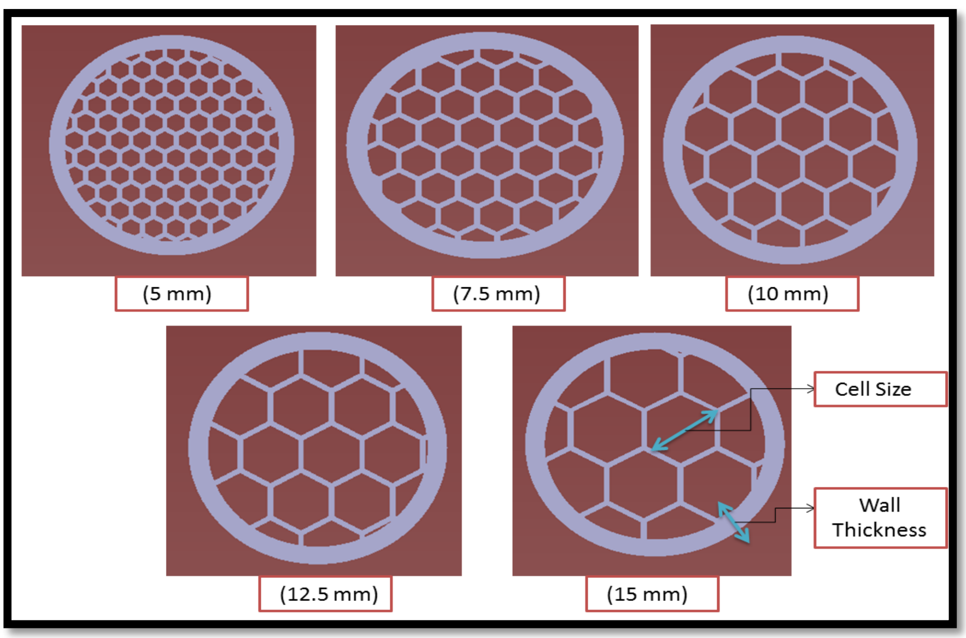


Fig. 30 CATIA modeled honeycomb cellular structure

These CAD models are then sent to Stratasys® FDM (dimension sst 1200es) for fabrication while keeping default processing parameters constant (Layer Thickness: 0.234mm, Raster angle: 45 degree, Orientation: 0 degree). This machine is developed and marketed by Stratasys Inc., 14950 Martin Drive, Eden Prairie, MN 55344-2020 U.S.A. The detailed machine specification is given in table below.

Table 4 AM machine Specification

Model material	ABS P400
Support material	Soluble (SST 1200es); breakaway
Build size	254 x 254 x 305 mm (10 x 10 x 12 in.)
Layer thickness	0.33 mm (0.013 in.) or .254 mm (.010 in.)
Size and weight	838 x 737 x 1143 mm, 148 kg (326 lbs.)
Temperature range	15˚C to 30˚C (59˚F to 86˚F)
Relative humidity range	30 to 70 percent, non-condensing
Heat emission	1080 Watts = 3686 BTU/hr typical, 1380 Watts = 4710 BTU/hr max
Workstation compatibility	Windows XP/Windows 7
Power Requirements	100–240VAC ~ 15 - 7A 50/60Hz 1200W

4.3 Measurement

Density:

The densities (equals to density per unit volume) of the solid structures were measured by dividing mass of structure with it's volume .Similarly relative density was calculated by the ratio of the density of the honeycomb structures to the density of fully dense ABSP400 material, taken here to be 0.98g/cm3. In real world, density of full dense ABSP400 is near about 1gm/cm3 (APENDIX A), however due to layer deposition nature of FDM process, experimentally it is found to be 0.98g/cm3.

Compressive strength:

Uniaxial compression tests are carried out using Instron 5582 at 1.0 mm/min loading rate. All the tests, done for measuring the compressive strength, are conducted in accordance with ASTM D1621 standards. A sample during the test along with loading direction is shown in Fig. 31

Fig. 31 – A specimen during compression testing

For microstructure analysis, a part having curve surface is cross-sectioned parallel to the building direction and an optical microscope with 400X resolution is employed to scan the surface. The optical microscope used in this study and the part is displayed in below Fig. 32.

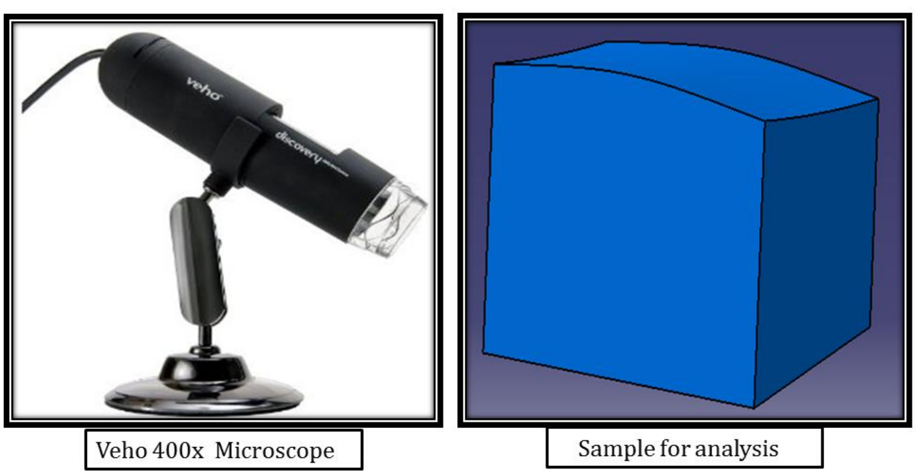


Fig. 32 Microscopic and Test sample

4.4 Result and Discussion

4.4.1 Mechanical properties

The honeycomb samples under compressive load behave as nonlinear elastic buckling which is well explained in [85]. Fig. 33 shows different stages of the buckling effect occurred in the sample during compressive testing.

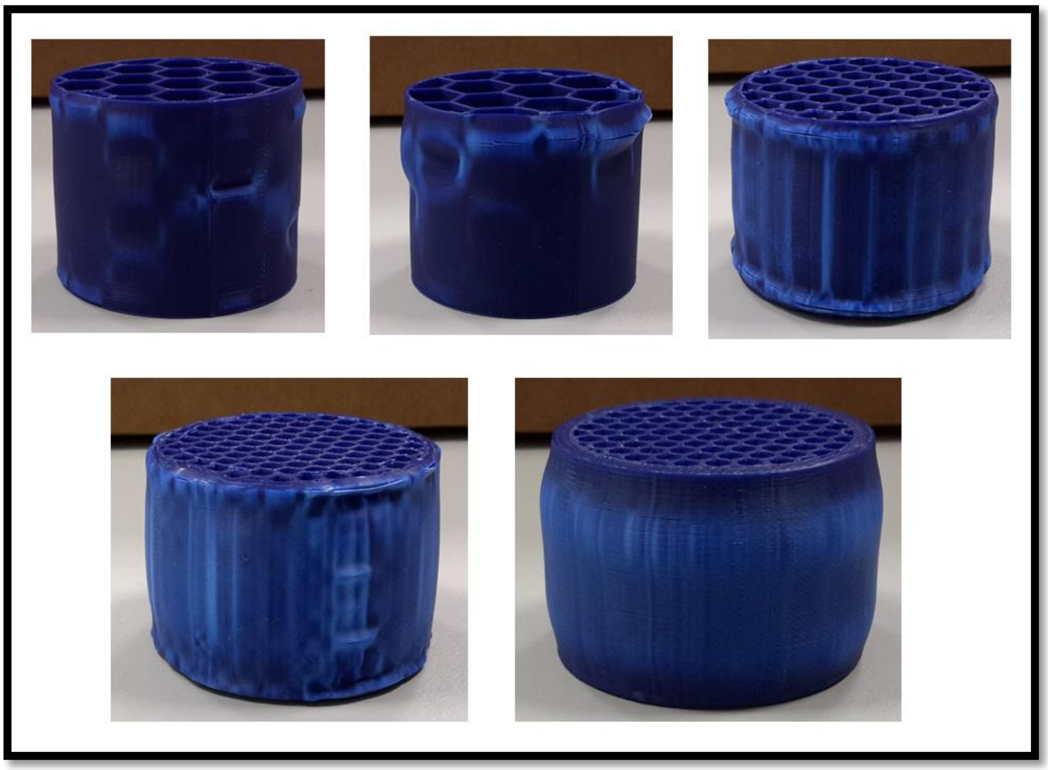


Fig. 33 Out-of-plane properties of honeycomb

4.4.1.1 Effect of unit cell size on the relative density

The relative densities of the honeycomb cellular structures with different unit cell sizes are shown in Fig. 34. The relative density of both wall thickness 1 and 3 mm decreases with increasing unit cell size. The honeycomb structure with the unit cell size of 5 mm has a relative density of 56%, which is higher than the relative density of the struts within the 15 mm cell size lattice structure, 36% (for 3 mm wall thickness). It is also noticed that at a fixed cell size, say

10mm, increase in wall thickness results in increase of relative density. This increasing trend may be the result of increase in material content for 3 mm thickness honeycomb structure in a defined volume.

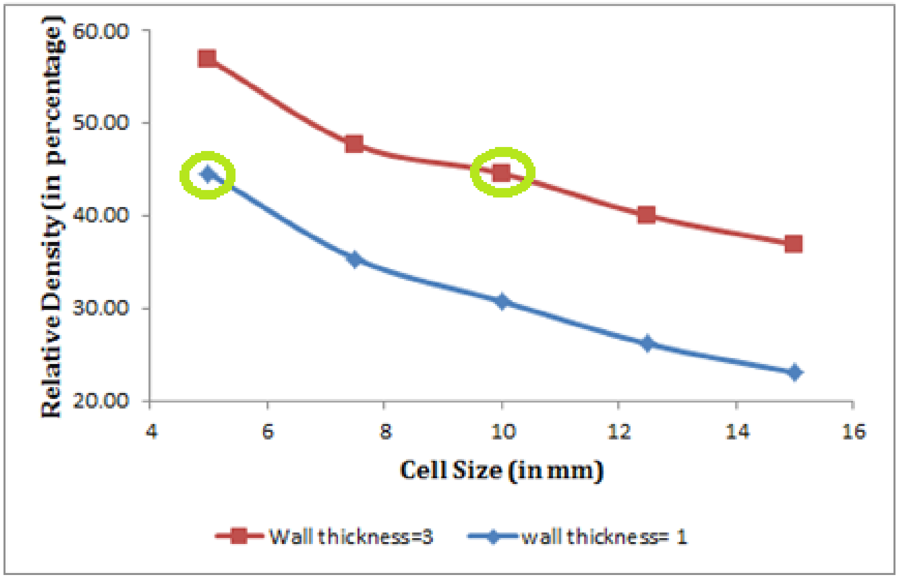


Fig. 34 Variations of the relative density with cell size at fixed wall thickness

4.4.1.2 Effect of cell size on the compressive properties

It is well known that the porosity, which equals to relative density, mainly determines the mechanical properties of cellular materials. Usually, higher relative density results better mechanical properties. Fig. 35 shows the compression strength of the honeycomb cellular structures as a function of cell sizes at the different wall thickness. Also at a fix cell size, Wall thickness = 3, offers more strength (16 MPa) than that of 1 mm thickness (13 MPa). This can be explained by computing amount of material inside the fixed geometry. Since 3 mm wall thickness contains more material (37 gm), it can sustain more load than 1 mm thickness (29gm) sample, thus more compressive strength.

A close look to the above figure depicts that the compressive strength for 1 mm thickness at 5 mm cell size is equal to 10mm cell size for 3mm thickness. This is just because that both of having same relative density.

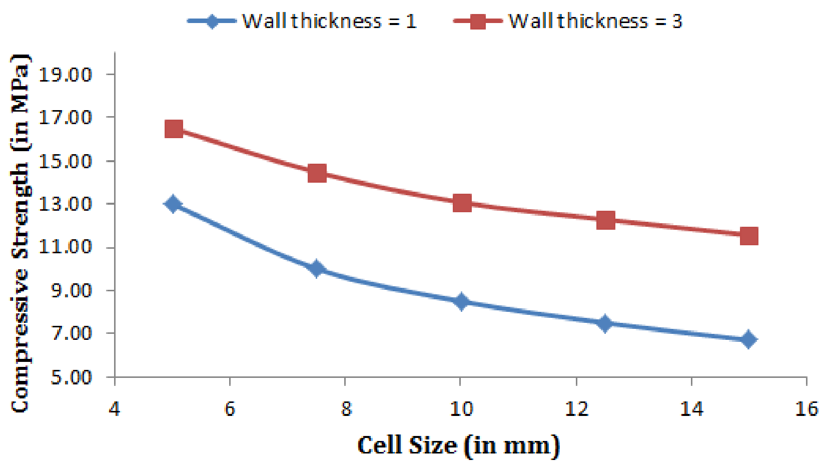


Fig. 35 Variations of the compressive strength with cell size at different wall thickness

Therefore it is confirmed by this experiment that compressive properties of the honeycomb structure directly depends on relative density which can controlled by varying cell size and thickness. To predict this strength Wierzbicki [86] has proposed an equation,

$$\frac{\sigma}{\sigma_o} = 3.25\left(\frac{\rho}{\rho_o}\right)^{1.7}$$

Fig. 36 shows a comparison plot between Wierzbicki model and the experimentally tested compressive strength of FDM printed honeycomb samples.

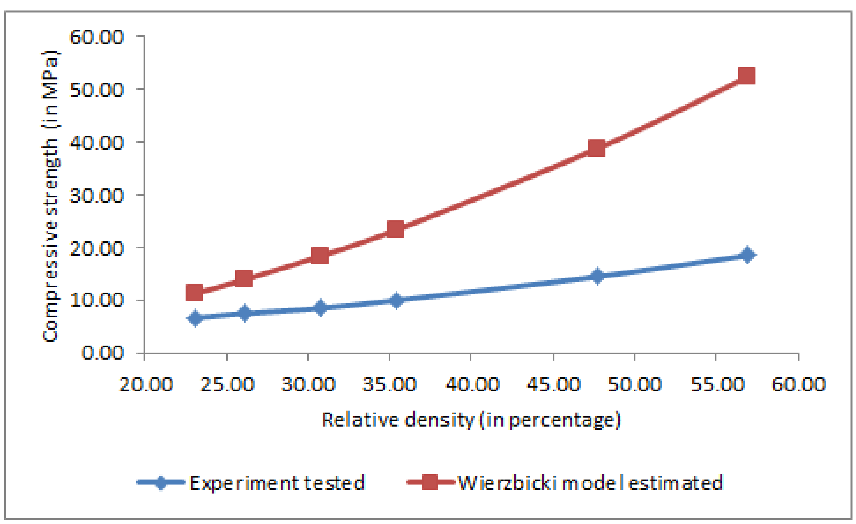


Fig. 36 Comparison of experimentally tested and Wierzbicki model estimated results

It is seen that there are differences between experimentally tested and Wierzbicki model estimated compressive strength. The differences in theoretical and experimentally tested values may be attributed to the layer by layer deposition strategy and residual stress inherent to the FDM-manufactured parts.

4.4.2 Optical microscope observation

The optical microscope an image of the cross-sections of honeycomb cellular structure is taken along the build direction (z axis) is shown in Fig. 37. It can be concluded from the micro image that the honeycomb structure made by FDM are conformal to the part curve shape and they have a good geometric agreement with the original CAD model.

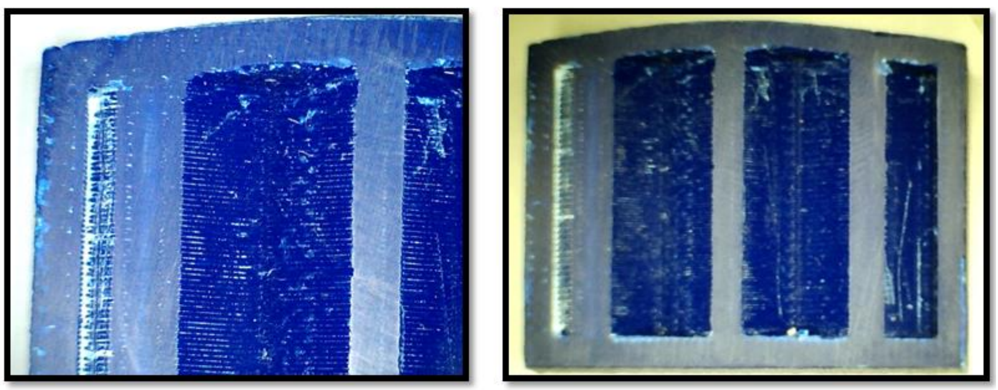


Fig. 37 Optical microscope image

In addition, these digital images indicate no defects or broken cells within the structures, confirming the ability of FDM to manufacture honeycomb cellular structures, which are very difficult or impossible to be manufactured by conventional manufacturing methods. Furthermore, they are well suited to the FDM's capabilities and can be constructed in a broad range of cell sizes. This verification would allow future development of even more advanced and functional cellular lattice structures.

4.5 Summary

This chapter evaluates the mechanical and microstructure characteristics of hexagonal honeycomb structures manufactured by FDM. These structures are designed by the design methodology explained in the previous chapter. Different honeycomb structures with varying cell size (5-10mm) and wall thickness are investigated in this study. The major findings are:

(1) The experimental compression strength of the honeycomb structure increases with the increase in cell size and wall thickness. The combination of these two parameters affects the relative density of the part, which is also a critical parameter for prediction of mechanical properties of the cellular structure. It has been seen that for same volume fraction, compressive properties is same irrespective of cell size and wall thickness.

(2) Compressive properties predicted by Wierzbicki model is found to be not in good agreement with experimental results. This may cause due to some of the reasons attributed to FDM process such as anisotropy nature of the produced parts, layer by layer deposition technique and the residual stress inherent in it.

(3) The micrograph images reveal that the hexagonal honeycomb structure produced by FDM is free from geometrical error and also there is no broken cell inside the part body. Moreover, this structure can adapt to curve surfaces without leaving any clearance in between the mating parts.

Chapter 5

DESIGN EXAMPLE

5.1 Overview

In order to validate the proposed design methodology, an industrial example is presented in this chapter. In this regard, re-design of resin transfer mold (RTM) mould (offered by a Portuguese company) considered here which is often used for composite manufacturing in various industries. The main objective is to save build material for the mould without sacrificing its strength (load of 3 bar pressure). Since honeycomb structures are known to provide high strength at relative low mass, it is intended to be used for this mould example. The detailed working procedure is explained in the following sections.

5.2 Resin Transfer Mold (RTM)

The Resin Transfer Molding (RTM) is one of the most promising technology available today for composite manufacturing. In this process, a reinforcement matrix is formed to the geometrical shape of the part to be produced. This preform is placed in a mold determining the final shape of the part. The dry preform is impregnated with a liquid matrix resin, injected at either one or several gates. After the curing of the resin, the part is de-molded (Fig. 38).

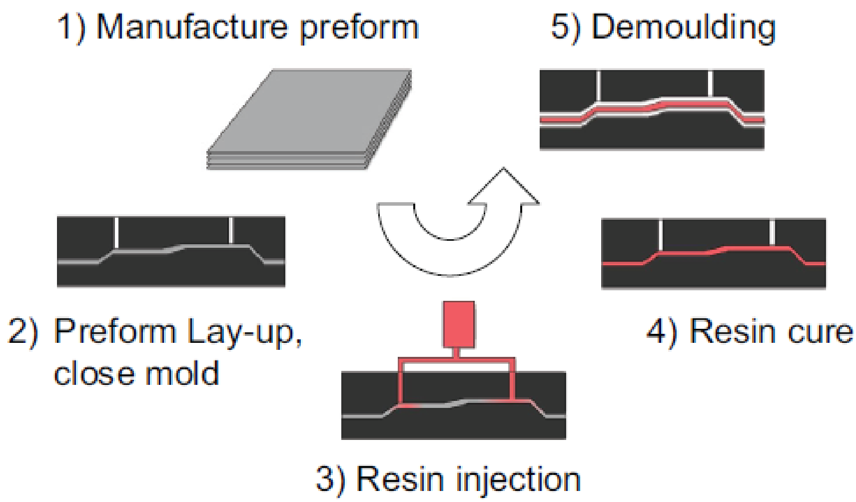


Fig. 38 Resin Transfer Molding Process [87]

RTM processes are capable to manufacture high geometrical complex parts and due to the comparably low cost of the raw materials and preforming technologies, it is applicable for medium size manufacturing series. However, for successful composite fabrication in RTM process, proper mold design should be done prior to processing. Moreover when mold is in complex in nature, it is much more critical to fabricate it within demand deadline by employing traditional manufacturing process. In this regard, AM seems to be a potential technology by offering customers a wide range of design freedom while designing their part along with variety of high grade materials at lower build cost.

Though it (AM) is capable to producing low cost (complex shape parts are cheaper to produce by AM, compare to conventional machining process) RTM molds in short span of time, introduction of cellular solids instead of bulky solid material, will further improve it's performance since they offer good mechanical and thermal properties over low material consumption.

In this chapter, hexagonal honeycomb structures are made with the help of our proposed method for RTM application and evaluated in terms of manufacturing cost with the standard aluminum mold.

5.3 Resin Transfer Molding (RTM) Setup

The RTM system used in this work, consists of two separate components, which optionally may or may not be used together for composites production:

- A heated press unit (model PRESSE 3508 SERIES – 15 kW): acquired from ISOJET Equipments (France). It consists of two heated plates of 500 x 500 mm with the maximum temperature of 200°C and the maximum pressure of 14 bars assisted by a pneumatic system (Fig. 39.a);

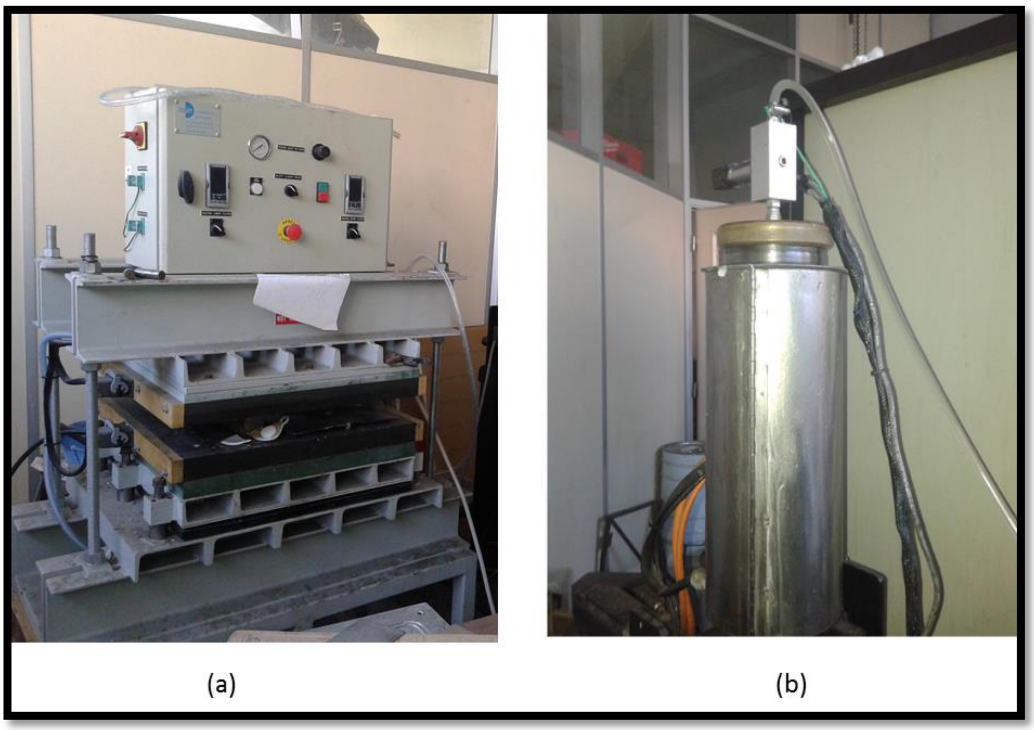


Fig. 39 Resin Transfer Molding (RTM) Setup

- RTM unit (model RTM PISTON 2006 – 3kW): acquired from ISOJET Equipment (France). It is composed of a heated injection piston (maximum volume at 3 litters) and a heated injection tube, a pressure control cell, a computer assisted control unit /data acquisition and a vacuum pump (Fig. 39.b).

5.4 Materials and Methods

Stratasys FDM (dimension SST 1200es) is used in this study, with default ABSP400 (APPENDIX A) material, to make RTM mold for an oar paddle application. Oar is a long stick with a wide flat blade at one end, used for rowing a boat (Fig. 40).

Fig. 40 Boat Oar Paddle

CAD models for the paddle's mold is designed in CATIA V5 and then it's scale down model is fabricated considering the FDM process capabilities and guidelines. The CAD modeled mold is shown in Fig. 41

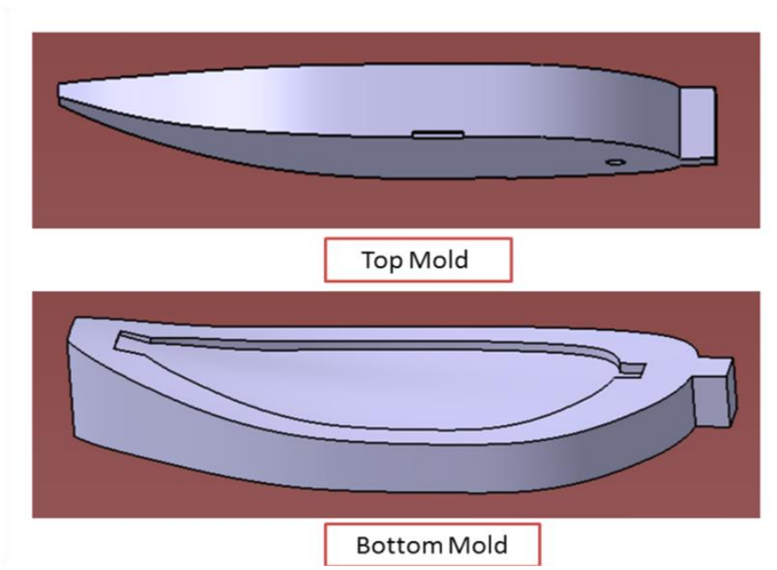


Fig. 41 Mold for Paddle

Before putting the ABS made mold in to use for RTM, we tested chemical stability of the ABSP400 with epoxy resin, used in molding (Fig.42). Staying stable for some long hours, it (ABS) finally proved it's inertness for the epoxy resin.

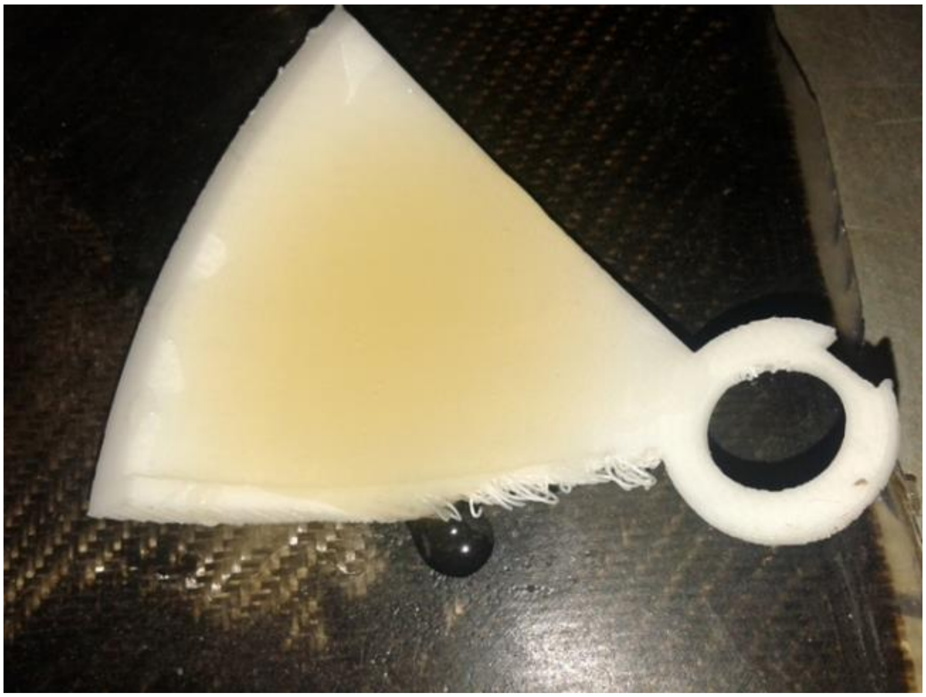


Fig. 42 FDM test specimen with epoxy resin

At first, we did a trail test by printing solid mold instead of the cellular mold for the oar paddle. The complete descriptions about this RTM test along with associated materials and machinery is explained below:

Step 1: Mold Making

In this step, solid mold for the Oar paddle is prototyped from the CAD model using stratasys FDM process. Proper inlet and outlet are designed in the mold for smooth flow of resin inside it. 4 mm width groove is also provided so as to prevent the spreading of resin when injected in the mold at high pressure. The complete FDM printed mold is shown in Fig. 43

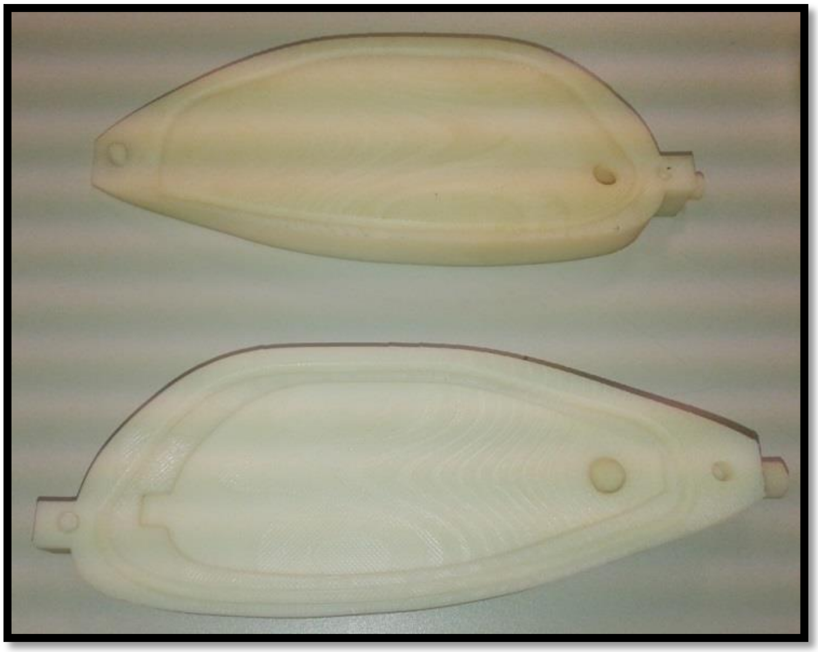


Fig. 43 FDM Printed Mold

Step 2: Reinforcement Selection

For oar paddle application, glass fiber reinforcement is selected due to it's good moisture resistance and high strength-to-weight properties. As per the desired size of paddle, it (3 pieces) is cut out from the bundle of fiber and then placed in between the molds (Fig. 44). The detail property about this glass fiber is attached as APPENDIX B.

Fig. 44 Glass Fiber Reinforcement

Step 3: Resin Preparation

A standard thermosetting liquid resin, with the commercial brand name Quires 406 PA is used in the matrix in the form of orthophthalic unsaturated polyester (UP). It is acquired from the company MR-Dinis dos Santos (Lisbon, Portugal) and its characteristics are presented in the APPENDIX B. Peroxide Methyl- Ethyl-Ketone (PMEK), also bought from same location, is mixed and stirred with the resin (10mm per 1 liter resin) properly as the curing agent of matrix (Fig. 45)

Fig. 45 Resin Preparation

Step 4: Injection

The mixture of resin and curing agent is injected at 20cc^3/min flow rate and 3 bar pressure into the mold; through RTM injection unit setup (Refer Section 5.2), till it comes out from outlet of the mold (Fig. 46). This confirms proper impregnation of resin with the reinforcement.

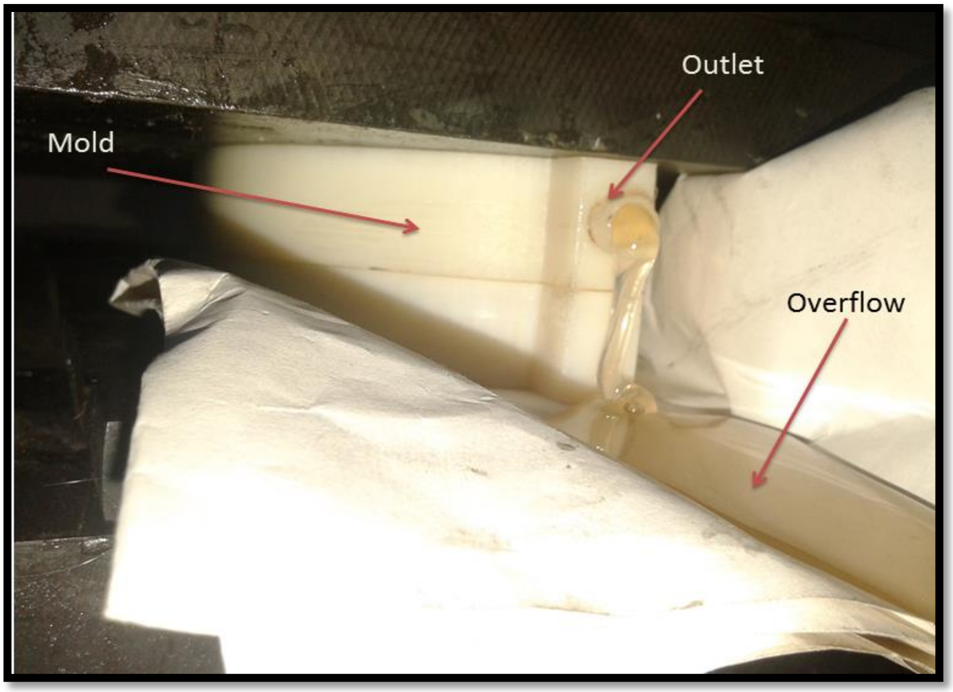


Fig. 46 Resin overflowing from the mold

Step 5: Curing

After injection, mold is kept under heated plates of the RTM machine for some hours (24 to 36)* for curing operation. Then it is taken out and composite is removed from the mold. The below Fig. 47 shows our glass fiber reinforced composite obtained directly from the mold.

Fig. 47 Glass fiber reinforced composite

Precautions:

- Mold is pre-heated for 30 minutes before performing the RTM test. This allows proper curing of resin, which results high strength composites.
- In order to get better surface finish in composite material, the mold surface is coated with a thin layer on resin before it's use.
- For easy removal of composite from the mold, we used a mold release agent (Honey Wax) before putting the glass fiber in to the mold.
- The FDM printed solid mold was successful for composite manufacturing accounting 336 gm of material. In order to reduce material content, we printed and tested the sparse infill mold, using the default setting in the machine.

Observations:

- The design and testing of sparse mold for RTM test (Fig. 48), concludes that when some load is applied by RTM pressure plates (about 3 bar) it transmits towards the edge of the mold. And if the edges thickness is of very thin, it can't transfer the load to the bottom part and fails.
- Loads count more at edge compare to the middle part of the mold.

Fig. 48 Crack deformation in the sparse filled mold

Therefore, considering DFAM approach, we designed honeycomb internally filled mold with wall thickness 10 mm and cell size of 10 mm. The choice of cell thickness and size in this research are based on mechanical characterization of honeycomb cellular solids

5.5 Cellular Mold

Since cellular structures show good performance at comparatively low volume of material, in this section we designed and tested our hexagonal honeycomb mold both experimentally and virtually by creating the similar RTM environment for it. . We used arbitrarily 10 mm cell size and 10 mm wall thickness to design the mold shown in Fig. 49 and 50 (drafting).

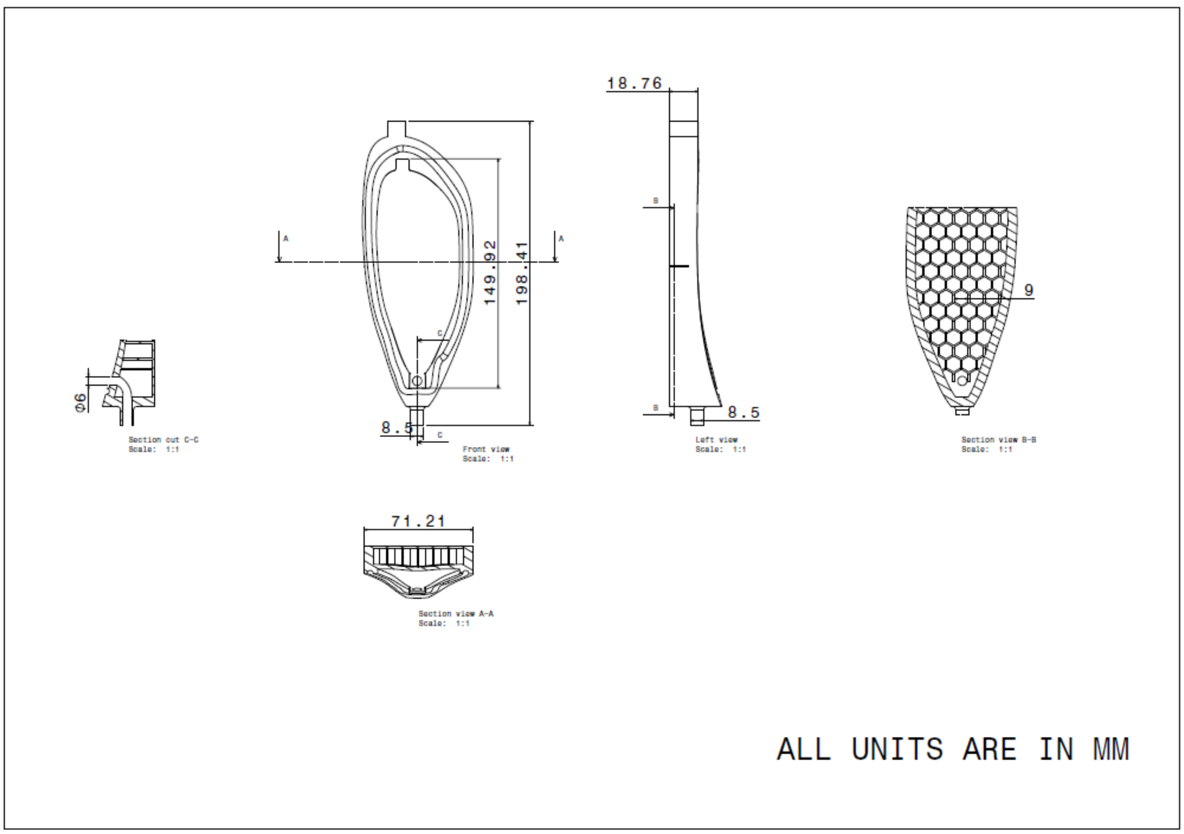


Fig. 49 Bottom mould drafting

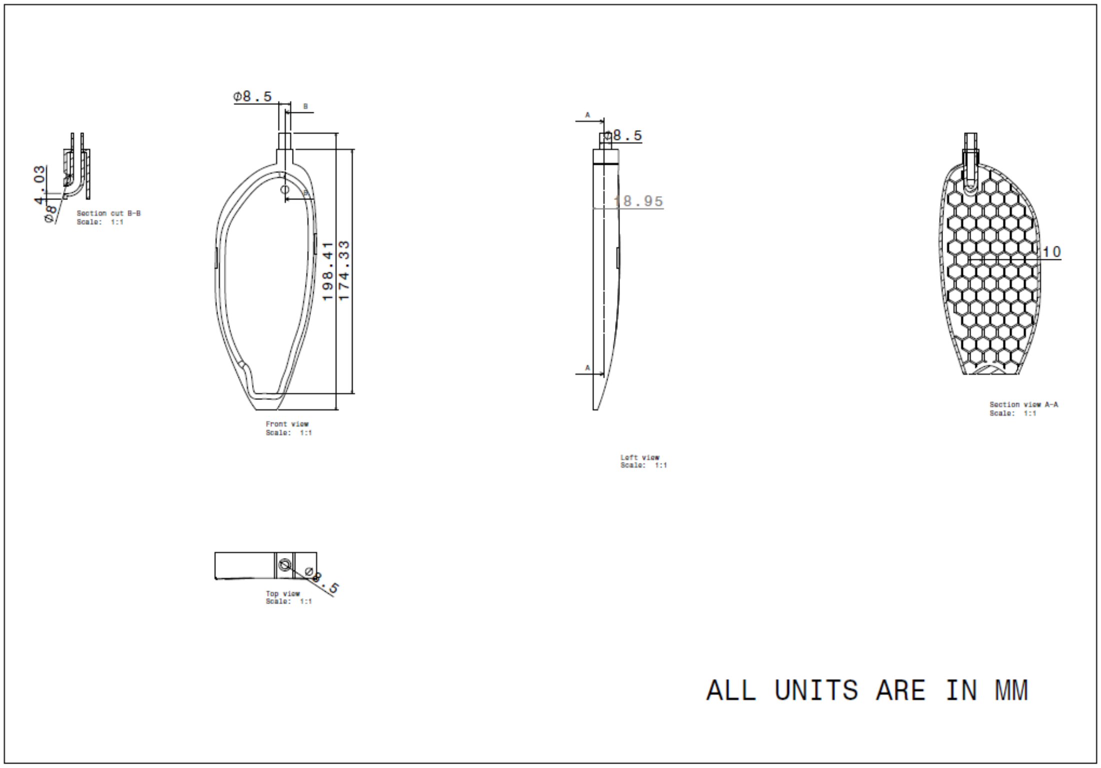
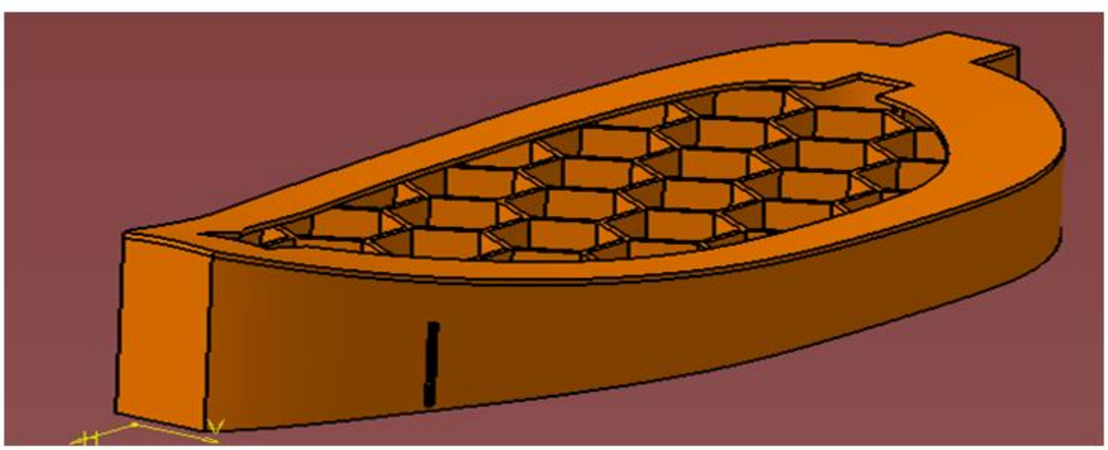
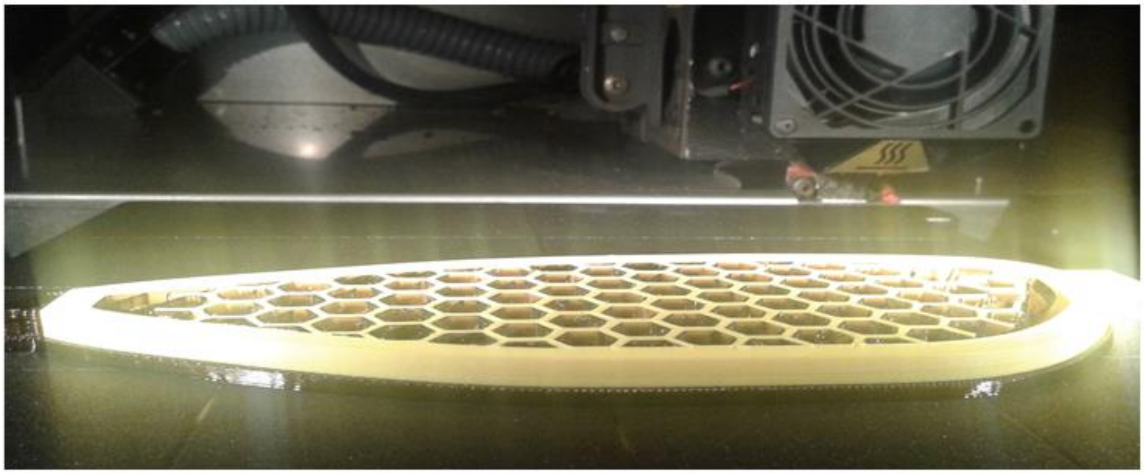


Fig. 50 Top mould drafting

Fig. 51(a) shows CAD model of the honeycomb mold while 46 (b) shows the same part while getting printed in FDM. Fig. 52 displays all the testing results of RTM process during the composite fabrication.



(a)



(b)

Fig. 51 (a) Internal layout of honeycomb filled mold (b) Honeycomb mold during printing

Fig. 52 Testing honeycomb mold

It can be concluded from the above experimental analysis, that our honeycomb mold design is safe and it can be used for production of composite via RTM process.

5.6 Result and Discussion

In this section, a comparative benchmarking analysis between three infill patterns of the mould such as solid, sparse and honeycomb is presented. It will be interesting to know their material count and build time. Table 5 shows these values along with their respective build times and weights.

Table 5 RTM mould characterization with three different infill patterns

Infill pattern	**RTM mould**	**Model Material (in cc^3)**	**Build time (hr:min)**	**Weight (gram)**
Solid	Bottom	169.66	7.42	333
	Top	166.77	7.29	
	Total	336.43	14.71	
Sparse	Bottom	53.96	3.52	102
	Top	50.71	4.05	
	Total	104.67	7.57	
Honeycomb	Bottom	111.59	13.25	228
	Top	71.12	11.44	
	Total	182.71	24.69	

From the above table, it is clear that solid mould is consuming more material followed by honeycomb and sparse. The time taken to print these moulds is also found to be in the same order as of material. It is also noted that though material and build time is minimum for sparse mould it failed during testing due to insufficient resistance to the applied force, whereas honeycomb mould is able to resist the load without any deformation. In this regard, direct 30% weight reduction is achieved which in turn will reduce the mould fabrication cost. For a clear understanding, bar graphs are also presented displaying the material consumption and build time consumed by these moulds.

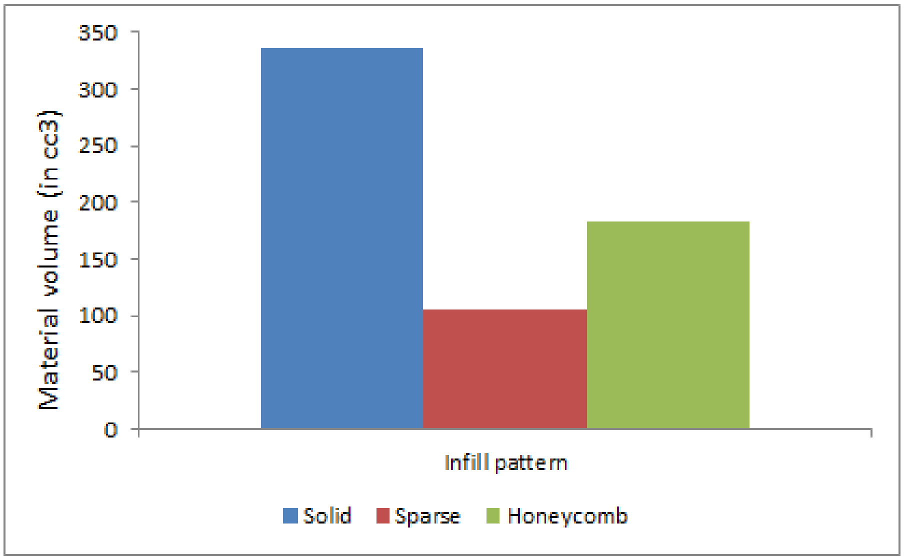


Fig. 53 Trade-off between material volume and infill pattern

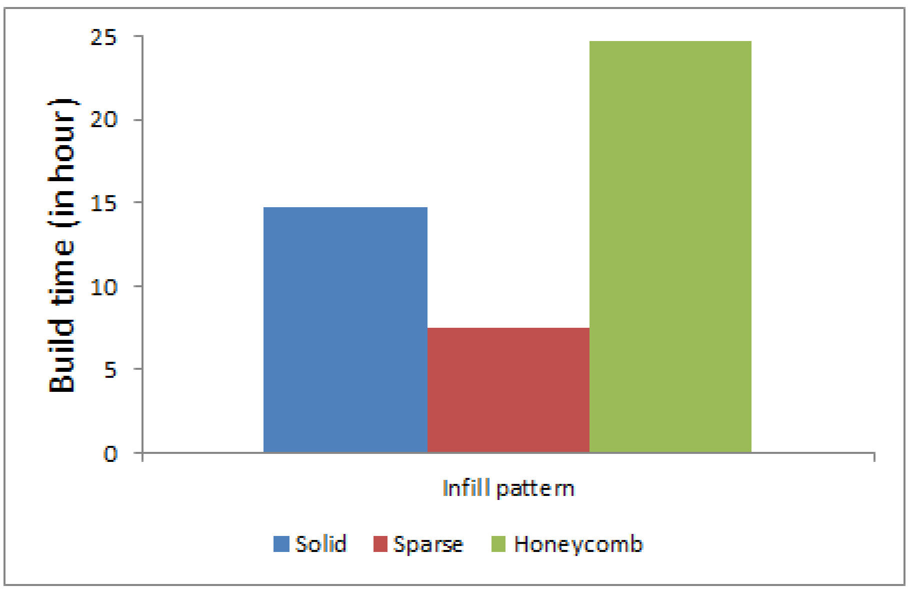


Fig. 54 Trade-off between build time and infill pattern

The above Fig. 53 and 54 portrays that though honeycomb pattern is able to reduce material consumption by 50%, though it takes more time to print which will increase cost of the prototype. The high build time associated with honeycomb structure can be explained by it's complex tool path for which FDM nozzle has to travel more distance compare to solid and sparse pattern.

5.7 Summary

In this chapter, a RTM mould is re-designed to save expensive build material by introducing honeycomb structure inside it. Due to complex shape of the mould, it is fabricated by FDM process since FDM has the ability to build complex prototype in a very precise manner without incurring machine tools and time. The major findings of this experiment are:

(1) FDM process is found to be an alternate way to produce complex RTM mould, which is sometimes difficult to produce by computer numerical control (CNC) machining. For instance, the RTM mould used in this research costs 280 € while produced by machining and 235 € by FDM (Cost analysis given by a Portugese mould making industry).

(2) Though FDM is able to produce complex shaped part, the part design must be optimized to bear the applied load. In this regard, for our RTM case study, solid mould is found to withstand the applied pressure whereas sparse mould got cracked during the loading in machine. Hence, hexagonal honeycomb (cellular) structures are introduced for the mould since cellular structures are known for the high strength-to-weight ratio properties.

(3) Result and discussion section revealed that, honeycomb filled mould is successful in composite production without any notification of part failure. Also the material consumption is found to reduce 50% compare to the solid mould. However, due to complex tool path it takes more time for printing compare to solid and sparse patterns. Therefore, there is a need to optimize the tool path planning for this honeycomb structure so that in future overall cost of the product can be minimized.

Chapter 6

EXECUTIVE SUMMARY AND CONCLUSIONS

6.1 Overview

FDM is a promising technology that builds part of any geometry by sequential deposition of the material extruded out from the tip of a nozzle in a temperature controlled environment. It has significant advantages in terms of elimination of expensive tooling, flexibility, and possibility of producing complex parts and shapes. One of the current challenges faced by FDM users relates to the cost of prototype and this is partly attributed to expensive process-able material. In this direction the present work emphasizes on the improving material distribution by introducing cellular solids since they offer significantly high strength at low relative mass.

6.2 Summary

The important findings of this thesis are summarized as follows:

- DFM is a useful approach to reduce, and hopefully minimize, manufacturing and assembly difficulties and costs. This engineering technique focuses not only on the design of a part but also on its producibility. The ease of producing a part with a manufacturing process can dramatically reduce its manufacturing costs. Producibility is not only affected by the manufacturing process but also by the geometry of the part, and many other properties of the part. To take advantage of this approach, it is necessary to identify their (additive manufacturing processes) specific manufacturing capabilities as well as their manufacturing constraints that must be respected.

- The need for minimizing the expensive build materials, fabrication time, energy consumption motivated the researchers towards designing cellular structures since a key advantage offered by these structure is high strength accompanied by a relatively low mass. However due to their complexity it is often difficult to generate using conventional manufacturing process. In this regard, advances in AM and CAD systems have allowed for the creation of complex geometries to a relatively high level of precision. From the study, it is found that AM is capable of producing this structure without any broken cells and geometrical defects.

- From mechanical characterization analysis, it is found that compressive strength of honeycomb is independent of height and cell size rather dependent upon their relative density. Relative density or volume fraction is defined as the volume percentage of the solid material in the cellular structure. It can be varied by controlling cell size and wall thickness. An increase in wall thickness and decrease in cell size, results increase in part density as well as relative density. It is also noticed that compressive strength of the cellular structure also increases with increase in relative density. This increasing trend is later confirmed with Gibson-Ashby model with some deviation in the plot. The deviation may be attributed to the residual stress and layer by layer deposition strategy of AM process.
- To save expensive FDM build material, designed honeycomb cellular structure is filled inside RTM mould and tested in compression. It is found that the honeycomb filled mould is capable of bearing the load of RTM test where sparse designed mould got cracked during the testing. Though this solid mould is able to sustain the load, but it consumes more material which is a major cause for high cost of the mould. In comparison, honeycomb mould reduces the material consumption up to 50% without sacrificing it's mechanical properties. With respect to build time, it is also noticed that these honeycomb mould, due to it's complex trajectory, takes more time to fabricate than the solid RTM mould.

6.3 Contribution

The method developed in this thesis allows leveraging the advantages of additive manufacturing for designing periodic cellular structures (honeycomb). Using this, cellular structures can be generated for hydro form and injection molding application, to reduce expensive build material consumption and production time. As per the author's knowledge, in future, the proposed method will have a greatest contribution towards sustainable and green product development. In addition, the design example presented here, would led the future design engineers for a low cost composite fabrication.

6.4 Limitations and Future Scope

- In this research, only hexagonal honeycomb, designed by FDM is tested for RTM application. In future, other category of cellular structure such as truss and lattice structure should be investigated to study their properties.
- Though honeycomb cellular structure is designed, it's optimization is not carried out yet for the given loading condition. It should be taken in to consideration for generating optimal part design.
- Tool-path optimization should be in future in order to reduce build time of the honeycomb structure which will enable low cost FDM products.
- In addition, the complete process should be integrated with the existing CAD platform, through an add-on installation, for quick and an easy part generation.

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APPENDIX

ABS Material Data Sheet

Physical Properties	**Metric**	**English**	**Comments**
Density	1.04 g/cc	0.0376 lb/in³	Grade Count = 3
Melt Flow	18 - 23 g/10 min	18 - 23 g/10 min	Average = 21.3 g/10 min; Grade Count = 3
Mechanical Properties			
Hardness, Rockwell R	103 - 112	103 - 112	Average = 110; Grade Count = 3
Tensile Strength, Yield	42.5 - 44.8 MPa	6160 - 6500 psi	Average = 44 MPa; Grade Count = 3
Elongation at Break	23 - 25 %	23 - 25 %	Average = 24.3%; Grade Count = 3
Flexural Modulus	2.25 - 2.28 GPa	326 - 331 ksi	Average = 2.3 GPa; Grade Count = 3
Flexural Yield Strength	60.6 - 73.1 MPa	8790 - 10600 psi	Average = 68.9 MPa; Grade Count = 3
Izod Impact, Notched	2.46 - 2.94 J/cm	4.61 - 5.51 ft-lb/in	Average = 2.8 J/cm; Grade Count = 3
Electrical Properties			
Arc Resistance	120 sec	120 sec	Grade Count=1
Comparative Tracking Index	600 V	600 V	Grade Count=1
Hot Wire Ignition, HWI	15 sec	15 sec	Grade Count = 1
High Amp Arc Ignition, HAI	120 arcs	120 arcs	Grade Count = 1
High Voltage Arc-Tracking Rate, HVTR	25 mm/min	0.984 in/min	Grade Count = 1
Thermal Properties			
Maximum Service Temperature, Air	88 - 89 °C	190 - 192 °F	Average = 88.7°C; Grade Count = 3
Deflection Temperature at 1.8 MPa (264 psi)	88 - 89 °C	190 - 192 °F	Average = 88.7°C; Grade Count=3
Vicat Softening Point	100 °C	212 °F	Grade Count = 1
Flammability, UL94	HB	HB	Grade Count = 3

APPENDIX B

MATERIAL DATA

RESIN

Characteristics	Quires 406 PA
Density	1.2
Viscosity at 25^{o}C (cPs)	600-800
Gel time at 25 ^{o}C (min)	14.5-15.5
Styrine content (%)	38-42
Acidity (mgKOH/g)	15-21

Reinforcement

Component Name	Glass fiber
Fiber Density	2600
Fiber Diameter	1.05E-04
Price	R$ 9,41

Catalyst

Component Name	BRASNOX
Density	1100
Price	R$ 9.3

Wax Blend for Industrial Mold Release

Product Name	Honey Wax
Physical State	Paste
Appearance	Yellow
Flash Point	40 ^{o}C
Boiling Point/Range	157-199 ^{o}C
VOC content	587 g/L
Specific gravity	0.78

LIST OF PUBLICATIONS

International Journals

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1) Panda Biranchi, Raju M V A and Biswal B.B. (2013) A General regression neural network approach for the evaluation of compressive strength of FDM prototypes", **Neural Computing and Applications**.(in press)
2) Panda Biranchi, Raju M V A, Biswal B.B., Leite Marco (2015) A novel approach for measuring volumetric error in Layered Manufacturing, Proceedings of the Institution of Mechanical Engineers, **Part C: Journal of Mechanical Engineering Science** (Under Review)
3) Panda Biranchi, Raju M V A, Biswal B.B., Leite Marco (2015) Design for Freedom of Additive Manufacturing using Advanced Computer-Aided Design Tools. **Additive Manufacturing** (Under review)

International conferences

1) Panda Biranchi, Leite Marco, Biswal B. B., Compressive property characterization of FDM printed cellular structures.(2015) **6th International Conference on Mechanics and Materials in Design**.(Accepted)
2) Panda Biranchi, Leite Marco, Biswal B. B., Journey from 3D printing to Direct Digital Manufacturing (2015). **International Conference on Direct Digital Manufacturing and Polymers**. (Submitted)
3) Panda Biranchi, Leite Marco, Biswal B.B., Cellular Arrangements for Additive Manufacturing: An Exploratory Study (2015). **MatCel'2015, Conferência de Materiais Celulares**.(Accepted)
4) Panda Biranchi, Raju M V A and Biswal B.B. (2014) Comparative Evaluation of Optimization Algorithms at Training of Genetic Programming for Tensile Strength Prediction of FDM Processed Part. **Procedia Material Science**, Vol.5, pp.2250-57
5) Panda Biranchi, Biswal B.B.and Deepak B B I V (2014) Integrated AHP and fuzzy TOPSIS Approach for the Selection of a Rapid Prototyping Process under Multi-Criteria Perspective, **5th International and 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR 2014)**